Towards the Holistic Assessment of Building Performance Based on an Integrated Simulation Approach

Thesis

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‘Buildings, too, are children of Earth and Sun’

Frank Lloyd Wright (1867-1959)

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CONTENTS

ABSTRACT

Preservation of energy resources, occupant comfort and environmental impact limitation are the key issues of modern and sustainable architecture. A multiple-view assessment of building performance at the design stage is therefore essential in order to prevent the delivery of buildings that do not comply with modern constraints. For more than a quarter of a century, building simulation programs have been developed to support non-trivial performance appraisals. In general, these programs deal with a small sub-set of the overall problem. To obtain a global view, solutions that permit stand-alone programs to inter-operate by sharing and exchanging common sets of information have therefore been developed. However, these solutions do not support dynamic information exchange and their complicated data management may lead to result inconsistency. Even if computer technology has rapidly evolved during the last few decades, no satisfactory level of integrated building representation has therefore been achieved so far, neither horizontally between different views nor vertically between all the processes that occur during the project life span.

This dissertation proposes a different approach that incorporates different views within a single program. The efforts undertaken in this work focused on (1) the design of the building data model, (2) its implementation into a single application and (3) its application to a case study to assess the building performance (thermal, lighting, acoustics, etc.) as well as occupant comfort and the environmental impacts generated by the building during its whole life span. Please note that cost estimation, construction planning or more subjective views, such as aesthetics, have not been considered in this work.
Chapter 1 points out the importance of using multiple-views during building design. It also gives the description of some constructive solutions developed in the past, which concurrently fulfil several assignments. It also illustrates the consequences of a lack of multiple-view assessment in appraising the building performance in modern architecture.

Chapter 2 reports different potential approaches to a multiple-view assessment of building performance. Although experimental methods are useful in various situations, the requirements of a holistic approach are better met by mathematical methods, especially computer simulation. This chapter scrutinises the approaches developed in computer simulation to provide a multiple-view assessment. Finally, this chapter analyses the capabilities of available integrated simulation programs, which leads to the conclusion that none of the available simulation applications can concurrently perform the assessment of the building performance (thermal, lighting, ventilation, acoustics), the occupant comfort and the environmental impacts over the whole life cycle of the building.

Chapter 3 focuses on the requirements of a digital representation of the building that enables a comprehensive representation of building elements with sufficient information to support a multiple-view assessment. It reviews the building representation developed since the 70's, especially the capability of two approaches to standardise the building representation. Scrutiny of the available approaches leads to the conclusion, that even though considerable efforts have been

undertaken, no standardised model that meets the requirements of a building representation that can support a holistic appraisal has yet been developed.
An important issue of this chapter is to define the assignments of the building representation, which supports view variations throughout the building life cycle in relation to performance views such as energy consumption, occupant comfort, room acoustics and the environmental impacts related to the construction materials and fuel streams over the whole building life span. This could be achieved thanks to the decoupling of the geometrical representation of the building and the description of the construction materialisation. This latter is structured by view, that are: hygro-thermal, optical, photo-colourimetry, room acoustics and environmental impacts. For each particular view, the physical attributes encompass a comprehensive set of attributes to become assessment methods independent. Finally, to support a detailed life cycle impact assessment, the environmental attributes are structured around a life cycle phase decomposition of the building life span.

The proposed approach could be implemented in the form of a new integrated application that enables a holistic assessment of building performance. However, within the time schedule of this work, it would not have been feasible to develop a new application starting from scratch. It was therefore preferred to select an existing building simulation program in which the proposed data model was then implemented, which is presented in Chapter 4. As a result of the selection procedure, ESP-r, a transient energy simulation system, which is capable of modelling energy and fluid flows within combined building and plant systems, was chosen. This chapter details the data model by view and ends with its technical implementation within the selected application. To support the holistic approach advocated in this document, the original functions of ESP-r have been extended to support the assessment of the missing views, which is the scope of the following two chapters.

Chapter 5 presents the methodology developed to assess in detail the environmental impact generated by a building during its entire life span. To take account of all impacts, a global balance of the materials and energy flows required during the building life has to be established. The presented methodology focuses not only on the impacts related to material manufacturing, but also on those of transport, assembly, maintenance, replacement and final disposal at the end of the building life. The proposed model meets the requirements of the life cycle assessment framework proposed by the International Organisation for Standardisation (ISO) for the assessment of the environmental impacts of a product.

Chapter 6 presents a second extension of the ESP-r capabilities, which enables the assessment of the room acoustics. The reverberation time is selected as an indicator to assess the room performance and is appraised with three different formulations of the diffuse-sound field theory, that are the Sabine, Eyring and Millington equations. The calculation includes the absorption of the enclosure boundaries, the occupants and furniture, and the enclosed air. The air temperature and humidity are also taken into account to improve the calculation of the sound speed and the air absorption.

Chapters 5 and 6 only present the methods used to assess the life cycle impact assessment and the room acoustics, but do not evaluate the conformance of the results obtained. This is done in Chapter 7, where a building case study is selected to demonstrate the applicability of the proposed approach. It presents the overall performance obtained for an office building as predicted by ESP-r enhanced with the development undertaken in this dissertation. The simulation results are compared with measurements monitored in the building during the post-occupancy phase. This chapter does not have the pretension to validate the simulation, but rather to analyse the conformity of the simulation results with in-situ measurements.

The document is structured in master chapters, which rapidly focus on the specificity developed in this work. To catch this dissertation globally, the reader requires particular knowledge in several domains. For the person who is not familiar with one of the tackled domains, specific vocabulary and concepts are summarised in appendixes.

RÉSUMÉ

La préservation des ressources énergétiques, le confort des occupants et la limitation des impacts environnementaux sont des problèmes clés de l'architecture moderne. Une évaluation pluridisciplinaire de ces performances est donc nécessaire lors de la phase de conception pour empêcher la construction d'un bâtiment qui ne satisfasse pas ces contraintes. Depuis plus d'un quart de siècle, des programmes de simulation ont été développés afin de permettre l'analyse de ces performances. En général, ces programmes traitent uniquement un sous-ensemble du problème global. Plus récemment, des solutions ont donc été développées afin de permettre à des programmes indépendants d'interagir, en amont de la simulation, par le biais d'un partage et/ou d'un échange de l'information nécessaire à la description du bâtiment. Cependant, ces solutions ne permettent pas l'échange dynamique de l'information lors des calculs. En outre, la complexité de la gestion de l'information transférée peut mener à une représentation du bâtiment qui diffère d'un programme à l'autre, ce qui peut amener à des résultats incohérents. Même si l'informatique s'est rapidement développée pendant ces dernières décennies, aucun niveau satisfaisant de représentation de bâtiment n'a donc été réalisé jusqu'ici, ni horizontalement entre les différents domaines analysés, ni verticalement entre les différentes phases du cycle de vie du bâtiment.

Ce document propose une approche différente qui permet une analyse pluridisciplinaire des performances du bâtiment au moyen d'un unique programme de simulation. Les efforts entrepris dans ce travail se sont portés sur (1) la conception du modèle du bâtiment nécessaire à une approche holistique, (2) l'implémentation de ce modèle dans un unique programme de simulation, (3) l'analyse d'un bâtiment existant du point de vue des performances (thermique, éclairage, acoustique, etc.), du confort des occupants et des impacts environnementaux générés par le bâtiment pendant toute sa durée de la vie. Il est à noter que l’analyse des coûts, du planing de la construction ou de domaines plus subjectif, comme l’esthetique, n’ont pas été considéré dans ce travail.

Le chapitre 1 montre l'importance de l'approche pluridisciplinaire lors de la conception d'un bâtiment. Il donne également la description de quelques solutions constructives, développées par le passé, qui affectent simultanément les performances dans plusieurs domaines. Il illustre également les conséquences fâcheuses que peut engendrer un manque d'évaluation holistique des performances dans l'architecture moderne.

Le chapitre 2 présente les différentes approches possibles permettant une évaluation des performances du bâtiment. Bien que les méthodes expérimentales soient appropriées dans certaines situations, les exigences d'une approche pluridisciplinaire sont mieux satisfaites par le biais des programmes de simulation. Ce chapitre détaille les approches développées dans ce domaine pour permettre une évaluation multi-domaines des performances du bâtiment. Finalement, une analyse des capacités offertes par les programmes existants mène à la conclusion qu'aucun d'eux ne peut effectuer en parallèle une évaluation des performances du

bâtiment (thermique, éclairage, ventilation, acoustique), du confort des occupants et des impacts environnementaux générés pendant la vie entière du bâtiment.

Le chapitre 3 se concentre sur les exigences requises par le modèle (numérique) du bâtiment afin de supporter une description suffisamment complète permettant une évaluation pluridisciplinaire. Il passe en revue les représentations du bâtiment actuellement disponibles, dont l'examen minutieux mène à la conclusion, que malgré les efforts importants ayant été entrepris, aucun modèle ne remplit les exigences d'une représentation du bâtiment qui puisse permettre une évaluation holistique. Un point important de ce chapitre est de définir une représentation qui pallie ces manques. Ceci a été rendu possible grâce à la séparation entre la description de la géométrie des éléments constituant le bâtiment et la matérialisation de ces éléments, i.e. les caractéristiques des matériaux de l'élément constructif. Ces derniers sont structurés par domaine, à savoir : hygro-thermie, optique, photo-colorimétrie, acoustique des salles et impacts environnementaux. Afin d'être indépendant des méthodes de calcul pouvant être utilisées dans un domaine, un ensemble complet des propriétés physiques propres à chaque domaine doit être inclus. Finalement, pour permettre une analyse du cycle de vie du bâtiment, les attributs environnementaux sont structurés par phase de vie d'un bâtiment.

L'approche proposée dans ce document aurait pu faire l'objet du développement d'un nouveau programme de simulation. Cependant, dans le laps de temps imparti pour ce travail, il n'aurait pas été possible de développer un tel programme à partir de zéro. Il a été préféré de choisir un programme existant dans lequel le modèle proposé a été implémenté, ce qui fait l'objet du Chapitre 4. Suite à une procédure de sélection, un programme de simulation performant et réputé (ESP-r), capable de modéliser dynamiquement les flux d'énergie et de matière dans le bâtiment, a été retenu. Le chapitre 4 décrit également en détail, à l'aide d'un langage conceptuel, le modèle développé pour ce travail, ainsi que son implémentation dans le programme sélectionné.

Pour défendre l'approche holistique préconisée dans ce document, les fonctions originales d'ESP-r ont été ensuite étendues afin de permettre l'évaluation des domaines manquants, à savoir : les impacts environnementaux et l'acoustique des salles. Le chapitre 5 présente la méthodologie développée pour calculer en détail les impacts environnementaux produits par un bâtiment pendant toute sa durée de vie. Pour tenir compte de tous les impacts, un décompte des flux de matière et d'énergie consommés pendant la vie du bâtiment est établi. La méthodologie présentée tient compte non seulement des impacts liés à la fabrication des matériaux, mais également ceux engendrés par leur transport, assemblage, entretien, remplacement, démontage et élimination à la fin de la vie du bâtiment. Cette méthode tient également compte des pertes de matériaux pouvant survenir lors des différentes phases de vie du bâtiment. Le modèle proposé satisfait aux exigences de l'évaluation du cycle de vie proposée par l'Organisation Internationale pour la Standardisation (ISO) pour l'évaluation des impacts environnementaux d'un produit.

Le chapitre 6 présente la deuxième extension d'ESP-r effectuée dans le cadre de ce travail, et qui permet l'évaluation de l'acoustique des salles. Le temps de réverbération a été choisi comme indicateur pour évaluer les performances de l'acoustique intérieure et est évalué avec trois formulations différentes de la théorie des champs-diffus, qui sont les équations (analytique) de Sabine, Eyring et Millington. Le calcul du temps de réverbération inclut l'absorption des surfaces, des occupants, des meubles et de l'air compris dans l'espace analysé. Il a également été tenu compte de la température et de l'humidité de l'air afin d'améliorer le calcul de la vitesse du son et de l'absorption de l'air.

Les chapitres 5 et 6 présentent uniquement les méthodes utilisées pour déterminer les impacts environnementaux et l'acoustique des salles, mais n'évaluent pas la qualité des résultats ainsi obtenus. Cette analyse est effectuée dans le Chapitre 7, sur un bâtiment existant afin de démontrer l'applicabilité de l'approche proposée. Après avoir effectué une analyse multi-domaines, en tenant compte des nouveaux développements implémentés dans ESP-r, les résultats simulés sont comparés avec des mesures effectuées in-situ. Ce chapitre n'a pas la prétention de valider les simulations, mais plutôt d'analyser la conformité entre les résultats obtenus par simulation avec les mesures in situ.

Chaque chapitre de ce document débute par un bref rappel des principes qui lui sont propres, puis rapidement se focalise sur les spécifications développées dans ce travail. Pour comprendre cette dissertation dans sa globalité, le lecteur doit avoir des connaissances particulières dans plusieurs domaines très différents. Pour les personnes qui ne sont pas familiarisées avec l'un des domaines abordés, le vocabulaire spécifique et les concepts de bases sont récapitulés dans les annexes.

CHAPTER 1

HOLISTIC BUILDING PERFORMANCE FROM ANCIENT TIMES TO THE PRESENT

'What is called modern, is maybe what is not lasting'

Dante (1472-1629)

Every major civilisation has developed an architecture with characteristic lines as specific as its language, costumes or folklore. For thousands of years, the human has developed architectural concepts to provide acceptable comfort in a specific environment, taking into account local climatic conditions, available construction materials, as well as cultural and religious aspects.
With modern architecture an important concern of the scientific community is to resolve specific problems the building industry is confronted with. But the necessity for an efficient construction industry has brought forward new architectural concepts, whose performance assessment required also an holistic approach. This chapter presents several ingenious systems developed trough time that could fulfil several assignments simultaneously and illustrates the consequences resulting of a lack of multiple-view[1] assessment in appraising the building performance in modern architecture.

1.1 HOLISTIC ARCHITECTURE IN ANCIENT TIME

Vernacular architecture, which can be regarded as a sustainable and natural contract between man and nature, is the fruit of imagination, years of evolution and climatic requirements [Fat1970]. It was limited to the local materials and techniques available at a given time. Transport was limited, which reduced the use of imported raw materials. This led to constructive concepts that took into account not only occupant comfort but also the local resources and the environmental impacts of the use of the construction. Vernacular architecture was able to provide many concepts to maintain comfortable conditions while striking a balance with the environment as it can be illustrated with the following examples.

[1] The term *view* is equivalent to the term *discipline, domain* or *functional aspects* used by various authors .

Simultaneously providing daylight and ventilation was an important issue, which was solved in different ways. In the Ancient Egyptian Empire (2635-2155 BC), it was not conceivable to bore through thick temple roof and walls. To solve the problem, small slots were pierced at the junction of the flat roof and the temple wall (Sphynx temple). Because of their size and location, these slots faintly lighted the upper part of the walls. In small temples or in dwellings, where the roof was thinner, small apertures were bored trough the roof-terrace, to improve daylighting and ventilation.
The New Empire (1550-1080 BC) found a way to improve the efficiency of these apertures by taking advantage of the level difference between roof-terraces. For instance, in the Ammon temple in Karnak, louvers were pierced into vertical slabs (walls) to provide better ventilation and allow the light to enter obliquely, which avoided glare problems as shown in Figure 1.1.

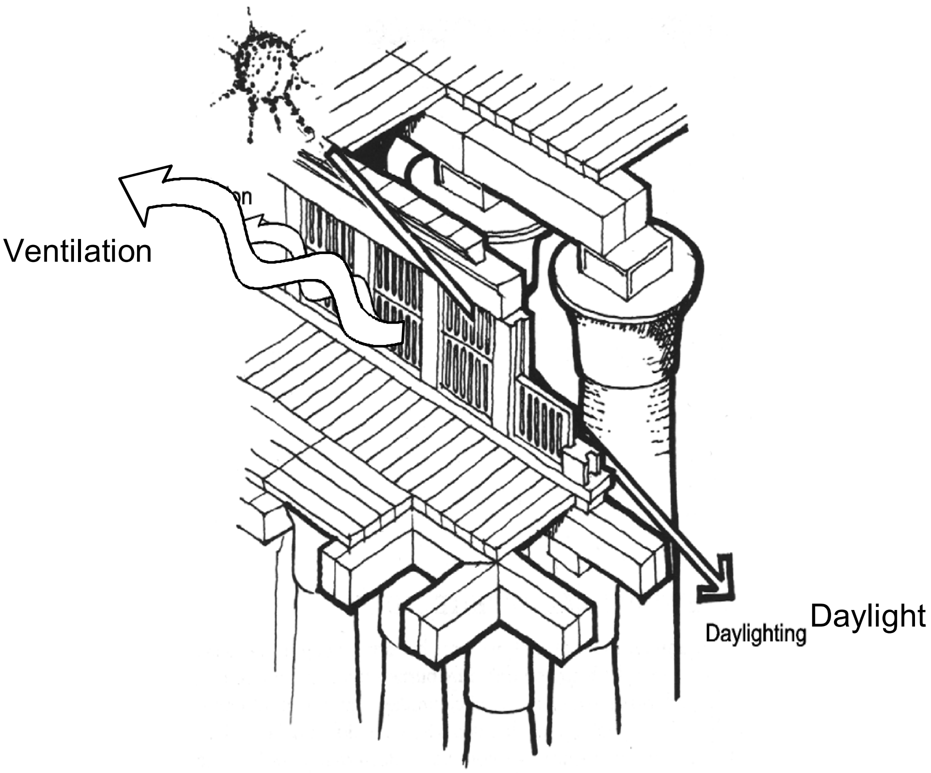


Figure 1.1 Clerestory of the Hypostyle Hall of the Ammon temple, Karnak (after [Moo1985]). (Amon.dsf)

The Summerians (Mesopotamia, 3000-2000 BC) are at the origin of several of the most outstanding human inventions, such as the wheel, the cuneiform writing or architectural concepts such as the vault. To avoid overheating, they covered roofs with about 1 meter of earth. But the load induced by the weight on the roof reduced its span, because palm-tree was used for the structure. Therefore, houses were narrow and long, which complicated their natural ventilation. Thus, the occupants' comfort was directly related to the structure. The evolution of this roof-terrace concept led to the famous suspended gardens of Babylon. They were located near wells, from which an astute system raised water to the roof construction for the irrigation of the gardens. Water evaporation reduced the ambient temperature and the roof cover reduced house overheating [Var1964].
For many centuries, vernacular architecture has been seen as the product of an evolutionary process in which the most suitable forms have survived by designing comfortable architectural spaces that respect local climatic conditions. This principle was also adopted by Marcus Vitruvius Pollio (ca. 70- 25 BC), roman architect, in his famous *On Architecture* [Per1979]. In his book V, which is

dedicated to the conception of theatre, he provided solutions for the daylighting, the natural ventilation, the thermal comfort and the room acoustics aspects. Vitruvius proposed that '*the spaces remaining between the beams, over the pilasters and the columns, are left open for light in the intercolumniations*' (Chapter 1.7). The natural ventilation and thermal comfort could be achieved by '*taking especial precaution that the forum be not exposed to the south; for when the sun fills the cavity of the theatre, the air confined in that compass being incapable of circulating, by its stoppage therein, is heated, and burns up, extracts, and diminishes the moisture of the body. On these accounts, those places where bad air abounds are to be avoided, and wholesome spots to be chosen*' (Chapter 3.1). On the room acoustics side, Vitruvius stated '*on this account the ancient architects, following nature as their guide, and reflecting on the properties of the voice, regulated the true ascent of steps in a theatre, and contrived, by musical proportions and mathematical rules, whatever its effect might be on the stage, to make it fall on the ears of the audience in a clear and agreeable manner. Since in brazen or horn wind instruments, by a regulation of the genus, their tones are rendered as clear as those of stringed instruments, so by the application of the laws of harmony, the ancients discovered a method of increasing the power of the voice in a theatre*' (Chapter 3.8). These concepts promoted by Vitruvius remained the chief reference on architectural matters until the Italian Renaissance.

Traditional Japanese and Korean houses are interesting examples of an architectural concept fulfilling several assignments simultaneously. The house walls consist of sliding doors made of wooden lattice panels covered with translucent rice paper as shown in Figure 1.2. During the hot and humid period, the facade may be widely open to invite the breeze. When the wind is too strong or too cold, the sliding doors are closed and the translucent paper still allows light to penetrate.

Figure 1.2 Traditional Japanese house (Kyoto).

The most typical building element of that culture is probably the tatami mat floor, made of packed straw about 4 cm thick and famous for its standard size of about 90 cm x 180 cm which influences the dimensions of the entire house plan. Tatami and other porous materials have the particularity to absorb humidity, which improve the thermal comfort. Furthermore, the porous material increases sound absorption at high frequency and creates a good meditation environment [Lee1996].

The shading device of these traditional houses is made of a fine lattice of bamboo, as shown in Figure 1.3. Placed at the external edge of the eaves, it provides efficient solar protection as well as a shaded walking path and allows the air to flow through the lattice.

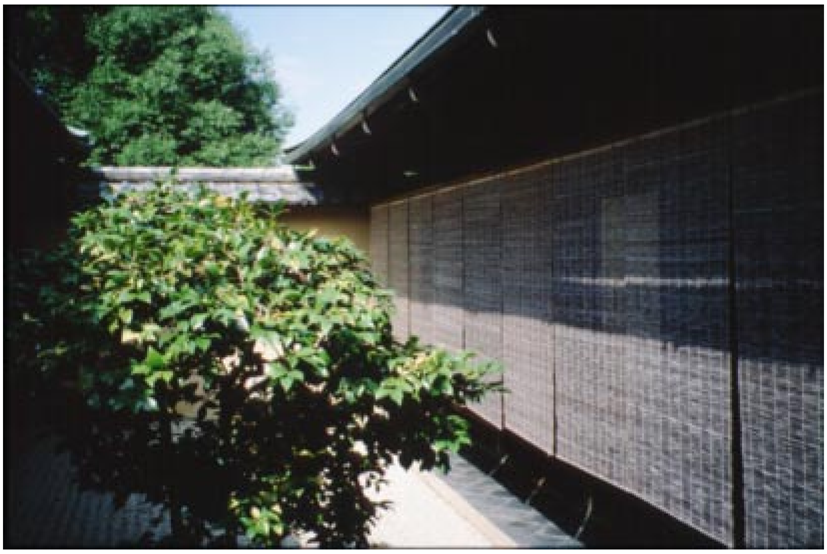


Figure 1.3 Solar protection in traditional Japanese house, made of a fine bamboo lattice (Kyoto)

This type of construction is appropriate for hot and humid climates, which use native materials wherever possible to reduce the environmental impact of human presence on the surroundings. Traditional Japanese house design can be seen as an architectural representation of culture: '*natural rather than artificial, assimilating rather than conquering, simple rather than complicated, pure, rather than condensed, calm rather than vivid, reserved rather than proud*' according to Kimura [Kim1996].

1.2 MOUCHARABIEH

Among all the solutions proposed by vernacular architecture, the most remarkable example of integration comes from the Arabian culture. The moucharabieh, which is a balcony closed by worked timber, was developed hundreds of years ago. At that time transport was limited and the use of imported raw materials was reduced [Iza1979]. As timber is generally rare in hot climates, the system was made of a precise assembly of small timber waste.

The moucharabieh is made up of three distinct parts as shown in the left part of Figure 1.4. While its bottom part is opaque, its middle part, at eye height, is made of a close-mesh net, which admits fresh air. It is based on local materials and techniques and has also a cultural role in that it provides Muslim women with privacy without isolating them from the external environment. The upper part of the moucharabieh is made of a wide-mesh net that allows daylight penetration. A shading system reduces solar gains in summer but allows sufficient daylight to save oil for artificial lighting when the sun is low on the horizon (end of day or winter). The moucharabieh has an other interesting application in a hot country. When porous pottery is placed just inside the moucharabieh, the air flows trough the apertures and cools down the liquid inside. This explains the name of the moucharabieh, derived from the Arabic *mashrabiyya* that comes from *Ma*, which means a temperate place and *Shrb,* which is a drink [Dep1985].

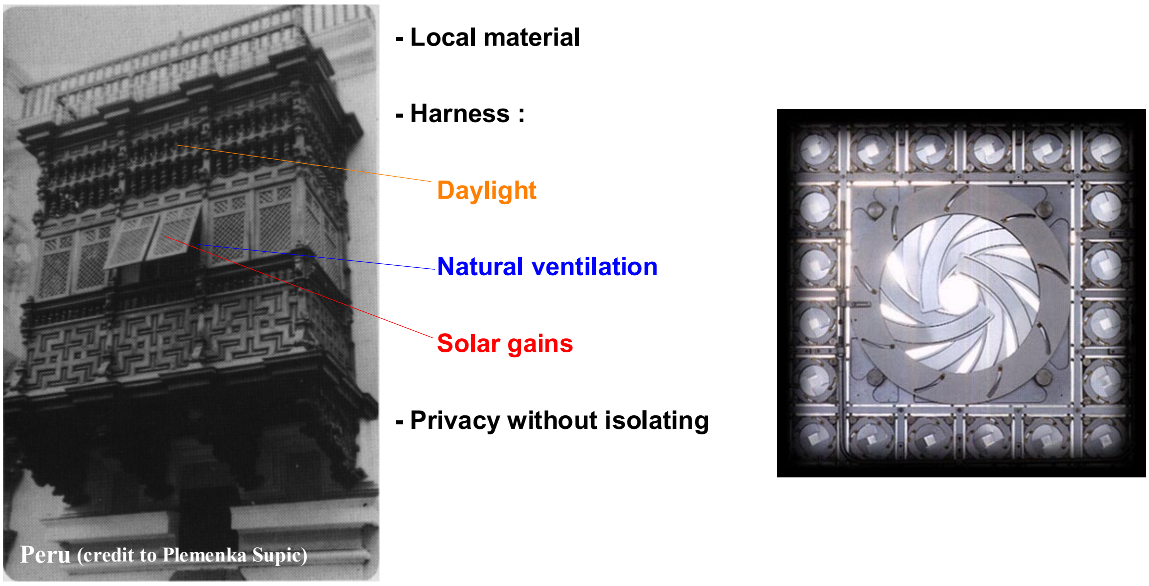


Figure 1.4 Traditional moucharabieh (left) and a modern adaptation (right) at the Institute of Arabic World, Paris.

By using different locations and sizes of aperture, the moucharabieh provides in a simple way the possibility to control natural ventilation, harness solar energy and daylight, and to control the severe climate of hot countries. All this leads to a constructive balance between occupant requirements and environmental impact. The advantages of the concept have led to its widespread use around the world in hot and dry climates. The development of the moucharabieh took several decades, but is an example of vernacular architecture that meets multiple-domain requirements with just one building component. The moucharabieh can be regarded as the ancestor of the 'integrated and sustainable' facade solution that is promoted at present.
Recently, architectural developments tried to adapt the moucharabieh concept to fully glazed facades (Institute of Arabic World, Paris) as shown in the right part of Figure 1.4. The building is made of hundreds of mechanical apertures encapsulated in the glass facade and the size of the apertures is controlled by the quantity of solar radiation. The natural ventilation that was originally part of the moucharabieh has been replaced by an air conditioning system, although the French climate is cooler than the north-African climate. Unfortunately, the efficiency of the new system was not as outstanding as the traditional concept.

1.3 MODERN TIMES

Erecting impressive constructions with a good indoor climate has always been a complex challenge for architects, engineers and contractors. Since the beginning of modern times, the range of materials available in the construction industry market has widened considerably and new constructive principles have emerged in parallel. From about 15 at the beginning of the 20th century, the number of generic construction materials has grown to approximately 350 [Khe1999]. Technical developments permit independence from local climate, provide everybody with an acceptable indoor quality and have rolled back the limits of the architects' imagination; almost any imaginable concept can be developed.

Anon (extracted from [Col1986]) states in 1930 that '*building has evolved on the assumption that people who spend a considerable portion of their lives in offices may reasonably be expected to* *demand cleanliness, daylight, air, a reasonable internal temperature, adequate and decent sanitary accommodation, efficient lifts, artificial light and power...'.*

At that time, there were no standards that promoted the holistic approach. Nevertheless, there are several examples of architects who have successfully integrated functional demands and good building performance and delivered buildings with pleasant occupant comfort. Among others, the Solar Hemicycle House is an example of such an application of the multiple-view approach during building conception. Frank Lloyd Wright designed this two-storey house for Herbert and Katherine Jacobs in 1944 at Middleton, Wisconsin (USA). The distinctive design aspects of this house are its characteristic *C* shape, a fully glazed south facade, and its bermed backside as shown in Figure 1.5.

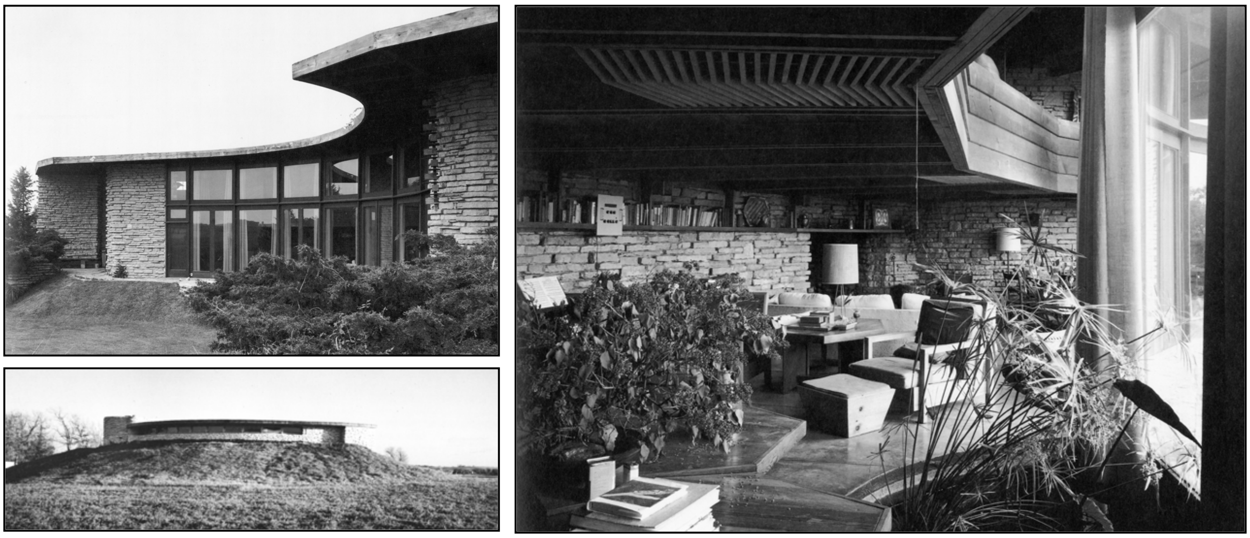


Figure 1.5 Different views of the Hemicycle House (extracted from [Fut1988] and [Jac1978]).

The South wall is made of floor-to-ceiling glass windows whose curved shape improve the efficiency of the facade in harnessing solar gains in winter when the sun travels from east to west. The roof has large eaves so that the south facade is protected from the direct sun radiation during the summer, and comes into the house in winter when the sun course is lower on the horizon, as shown in Figure 1.6.

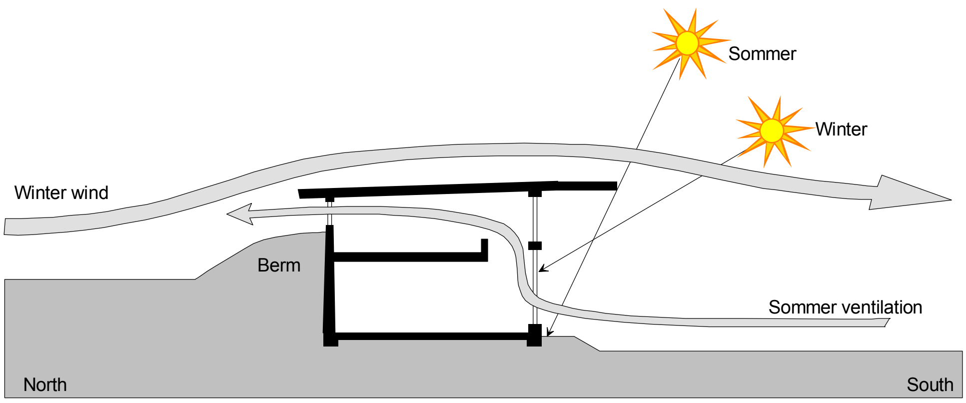


Figure 1.6 Cross section of the Hemicycle House, showing the eaves efficiency, the principles of cross ventilation during the summer period and the protection against the northern wind thanks to the berm. (coupe.dsf)

The back wall goes up about 1.2 meter above the berm and has a strip of windows about 60 centimetres high which wraps all around the outer north facade of the house. The buried backside reduces the heat losses through the house envelope during the winter period and has a curved shape that increases the structure resistance to the pressure of the earth berm.

The building has a high thermal inertia thanks to the use of apparent limestone for the house structure, floor and walls. The irregularly laid of limestone bricks not only relate the building interior to the natural external environment but also increase the apparent surface of massive material for thermal storage purposes.
The second floor is a suspended balcony, whose front sits about 1.2 m back from the south window wall and allows heat to rise from downstairs to heat the upper floor during the winter heating season. During the summer, the backside (North) and the south windows are open to allow a cross ventilation of the house as shown in Figure 1.6. The combination of this natural ventilation and the high thermal inertia of the floor and walls provide a pleasant thermal comfort during the warm period. The windows are closed and the bermed facade acts as a windshield during wintertime, when there are dominant cold blows from the North. In combination with the *C* shape, they create a sheltered patio.

Finally, the use of native construction materials (limestone and pine) and a suitable application of the passive solar concepts entails that the Hemicycle House is a good example of a sustainable building providing good occupant comfort at low energy cost although it was erected thirty years before the ‘oil shock’.

The holistic appraisal of the building performance as promoted by Anon or Wright was very limited at that time. Observations were made, but there were no standard requirements for building design. After the Second World War, standards mentioned timidly the necessity to ensure integrated occupant comfort in building design, such as the French *Règlement de la Construction, article 2*, in 1950's, which required taking into account acoustics and thermal insulation in buildings [Rou1975]. But it was just a desired objective and no limit value was required. At that time Eichler [Eic1952] seemed to be the first to scientifically analyse the concurrent improvement of thermal and acoustic performance ensuing from the use of facade insulation. This domain of research attained its pinnacle in the 1970's, when energy conservation and environmental considerations raised in importance due to the oil shock. The energy crisis served as a warning to the governments of the developed countries that oil energy is not inexhaustible and should not be wasted, and promoted the improvement of the building envelope insulation. For instance, Figure 1.7 shows three variants of a double facade typology. The left variant does not have any insulation, in the middle variant the air gap is filled with a mineral insulation of 5 cm, while the right variant uses 10 cm of insulation. For each variant the thermal and acoustics insulation are indicated. The thermal insulation is expressed by the thermal transmittance, known as the U-value, which gives the rate of heat loss through an element. The acoustic insulation is represented by the weighted apparent sound reduction index (*R'w*), which gives the sound level reduction obtained by the element. As can be seen in Figure 1.7, the filling of the air gap with a mineral insulation divides by a factor two the heat losses through the facade and improves the acoustics insulation by 3 [dB]. The thicker the insulation, the better the thermal and acoustics insulation.

During the oil crisis, several studies analysed the concurrent improvement of thermal and acoustic performance ensuing from the generalisation of facade insulation and the reduction of air leakage paths trough the external building shell, such as [Gös1975; Mei1980; Sab1975]. These themes are still topical [Dia1986; Koc1997].

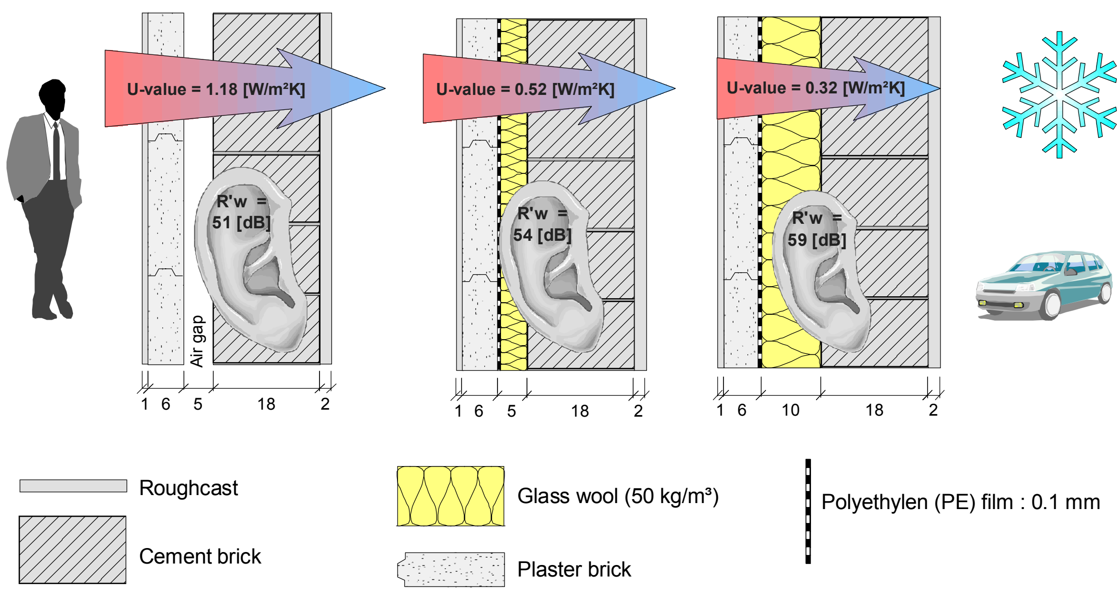


Figure 1.7 Thermal and acoustics performance resulting from the use of mineral insulation. **(acoustic & thermal insulation.dsf)**

Nevertheless, since the oil shock, i.e. in less than thirty years, the global energy production has increased by approximately 50 percent and tripled in the developed countries, in which fossil fuels represent 90 percent of the energy consumption [ICR1997]. Efforts to reduce the environmental impact of buildings have focused primarily on efficiency in terms of energy consumption during the utilisation phase. But if the ecological aspects of the construction are not explicitly taken into account during the conception stage, the retained solution will directly influence the environmental impacts generated by the building. In recent times, environmental concerns have also focused on environmental impacts generated by materials and processes (including transport), which must also be accounted as an environmental cost of the building construction. In the 1990's, the awareness of the human's activities on his environment regained attention. The impacts generated by the building during its whole life span were added to physical and financial considerations, as illustrated for instance by Erlandsson [Erl1997].

Among the building components, glazing probably assumes the largest number of functions simultaneously. It creates an acoustic and thermal protection with respect to the external environment, provides a view and natural ventilation, and allows the visible and solar radiation to penetrate into the building, which directly influences the heat loss and solar gains of the building. Although it took many years for human beings to define the best proportion of a window, adapted to the local climate and architectural traditions, a modern architect has the technical possibility to increase the window size until it occupies the totality of the envelope. For such buildings, a multiple-view assessment is important in order to reduce overheating and glare problems due to the solar gains [Etz2000; Lam1995; Lee1998; Pra1997].

Multiple-view assessment can be used as a commercial argument to put forward the advantages of a material and can also have surprising applications, such as the evaluation of thermal and visual comfort assessment of pavement used during foot drills [Ann1997]. But the holistic assessment is an important issue, which is unavoidable in modern architecture and must be conscientiously followed; otherwise, unacceptable building performance may result.

1.4 CONSEQUENCE OF A NON-HOLISTIC APPROACH

Several recommendations already pointed out the importance of the holistic approach during the building conception, such as the Union Suisse pour la Lumière (USL) [USL1974], which requires from the “ *architects to co-ordinate sufficiently early, in relation with the global project, the lighting, air-conditioning and acoustic techniques*”. The following example illustrates the consequences of having not simultaneously assessed the building's performance from different viewpoints.

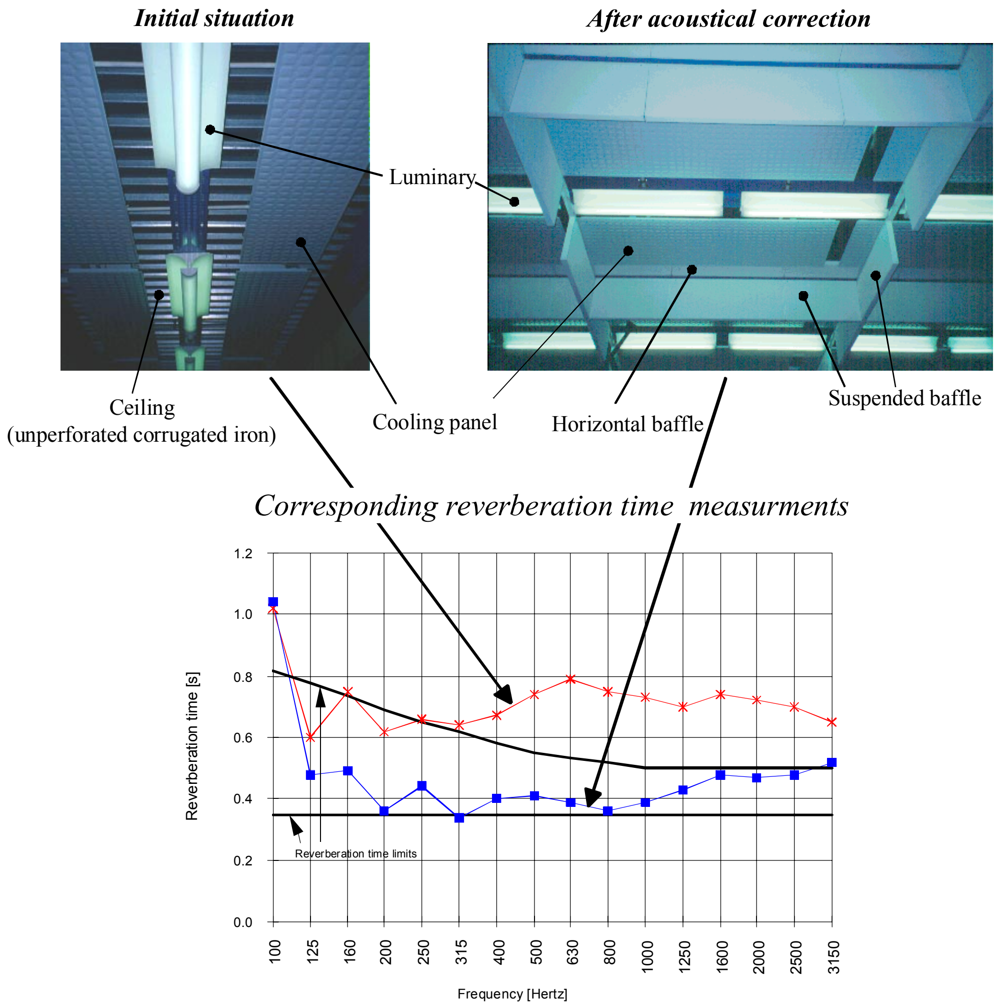


Figure 1.8 Example where a room acoustics problem has occurred due to a lack of a holistic approach during the design stage. The left picture shows the original situation, where the ceiling of the open-plan office was made of unperforated corrugated iron with cooling panel, which led to an excessive acoustic reverberation. The right picture shows the same ceiling where absorbent baffles have been added to improve the room acoustics of the office. **(ubs.dsf)**

Figure 1.8 shows the acoustic performance of an open-plan office room with a large glazed facade and a cooling ceiling where the thermal, ventilation and lighting systems were correctly appraised. As the room's acoustic performance during the design stage was not appraised, the low acoustic absorption of the cooling ceiling was not taken into account, which led to an excessive acoustic reverberation.

The absence of a holistic approach necessitated a post occupancy acoustic correction. This correction had to reduce the reverberation time of the open-plan office without affecting the other systems. It had to provide a sufficient equivalent absorbing area without reducing the efficiency of the cooling ceiling and the desk illumination. Replacing the initial system with a cooling suspended ceiling that integrated the luminaries and was perforated for acoustic purposes was financially not acceptable. Due to the office configuration, covering the walls with absorbent material was not possible because they were mainly transparent. The only remaining and also the most efficient location where the problem could be solved was the ceiling. The solution that was finally adopted used suspended baffles, whose dimensions and locations were chosen so that they would not affect the efficiency of the cooling radiant panels and artificial lighting system as shown in the right part of the Figure 1.8. This example illustrates the risk incurred by not adopting an integrated approach during the design phase, which can cause unacceptable performance that is generally difficult to resolve once the building is occupied, can be expensive in time and money and lead to a building environment that is not comfortable.

It is interesting to note that a similar problem was studied by Newman [New1952] in the 1950's when excessive acoustic reverberation was shown to be due to the massive use of translucent acrylic ceilings used for artificial lighting. To meet acoustic and lighting needs, Newman proposed to replace acrylic panels with absorbent panels as shown in Figure 1.9. For the interested reader, the Appendix A list some other combined multiple-view effects that may be considered during the design phase of a building.

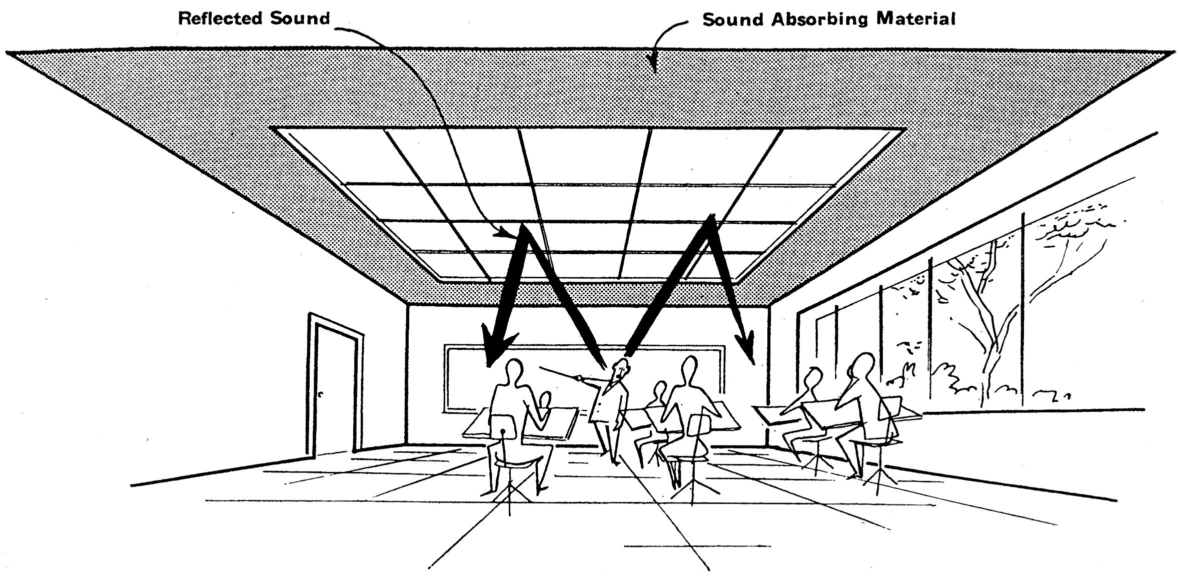


Figure 1.9 Antinomy between acoustic reverberation and lighting performance by the massive use of acrylic ceilings in office buildings (Extracted from [New1952]).

Whatever the building concept is, the design phase, during which the building's concept is defined, a site is selected and construction materials are chosen, has a major influence on the building performance that will determine user acceptance [Eld1981; Han1997; Mah1996a]. A holistic approach is not only recommended for new building design, but can also be used to assess the performance of existing buildings, as for instance the Mackintosh School of Architecture [Han1997] or a survey of occupants comfort [Har1999].

In summary, this chapter has shown, that through time, architecture has developed ingenious constructive solutions that could fulfil several assignments simultaneously. The limitation of available materials and construction processes was compensated by long experience leading to a constructive balance between occupant requirements and environmental impact.
Technical developments and a sudden explosion of available construction materials during the 20^{th} century have rolled back the limits of architects' imagination and they have now the ability to develop almost any imaginable concept. To meet the expectations of modern architecture, researchers have to develop complex and specific solutions. However, this complexity calls for a holistic appraisal of the building performance during the design phase to ensure a construction that meets with general acceptance. The next chapter presents a critical review of available solutions and describes the assignments of a multiple-view assessment.

CHAPTER 2

INTEGRATED SIMULATION

At all times, the analysis of physical phenomena was dependent on technical developments and scientific knowledge. In the past, performance assessment relied on thumb rules and hand calculation. At present, the advent of building simulation programs has enabled non-trivial performance appraisals. The current generation of applications for the assessment of building performance ranges from simple spreadsheets based on simplified calculation methods to advanced programs, which allow the simulation of transient physical processes using complex numerical methods. In general, these programs deal, however, only with a small part of the overall problem.

Advanced architectural developments require an integrated approach to design. The domains of heating, lighting, ventilation and acoustics, for example, are often closely related and it is only by taking into account their interactions that a complete understanding of building behaviour can be obtained. This chapter begins with a comparison of various methods developed to perform a multiple-view appraisal of building performance. The chapter follows with an analysis of the different simulation program types that support multiple-view assessment. Finally, the most common simulation tools available on the market are compared.

2.1 ASSESSMENT OF BUILDING PERFORMANCE

At present, building performance can be appraised using many different techniques:

- Scale model can be used when the physical phenomena are not scale dependent or if the loss of accuracy is acceptable compared to the studied parameters, such as for lighting and acoustics. Scale models are cheap and can be tested under real conditions. Under artificial conditions, experiments are reproductive, which facilitates variants comparison. But, measurement errors may originate from scale model effects, level of detail and material effects. Moreover, energy consumption and environmental impact assessment is not accessible on a scale model.

- Full-scale experimentation is probably the oldest method used to appraise a physical phenomenon and supplies incontestable information. It is appropriate to collect information when no mathematical model exists or to compare a mathematical model with in-situ measurements. The advantage of the experimental approach is that it deals with reality and therefore automatically includes simultaneous contributions when different phenomena are interacting; moreover errors are limited to experimental procedures. However, it is onerous and time consuming.

- Many physical phenomena are predictable with complex mathematical models. Under appropriate and acceptable assumptions, complex equations can be simplified with certain assumptions to provide analytical solutions, which shows the degree of dependence between the parameters and the relative importance of the various terms. These analytical equations are simple but must be used within the assumption frame, otherwise it will lead to an erroneous analysis and inaccurate results.

- The emergence of pocket calculators and personal computers has made possible the numerical resolution of complex physical phenomena that do not have analytical solutions. The model implementation may be complex and may require a calibration/validation of the model, but the numerical approach simplifies the scrutiny of parametric analysis.

A holistic approach to building design requires a method to estimate the performance that will result from the interactions between the different domains. As can be seen from Table 2.1, which summarises the capabilities of the available approaches, full scale experiments and numerical simulation are suitable methods for multiple-view analysis, because both integrate the complex physical phenomena and today they can address the same problem. As the experimental approach is time consuming and expensive, it can be argued that computer simulation is the preferred option for the holistic appraisal of design options.

Approach	Type	Advantage	Disadvantage
Experimental	Scale model	• Low cost • Reproductive experiment • Comparison of variants	• Scale effects • Model approximation/error • Measurement errors
	Full scale	• Complex phenomenon • Global analysis	• Time consuming • High cost • Measurement errors
Mathematical	Analytical	• Ease to use	• Simplified model
	Numerical (computer)	• Complex model • Fast calculation • Comparison of variants	• Request calibration/validation • Model might be complex • Model approximation/error

Table 2.1 Comparison of building physics simulation approaches.

2.2 EVOLUTION OF MULTIPLE-VIEW COMPUTER SIMULATION

Two thousand years ago, Vitruvius [Per1979] stated that plan, elevation and perspective were the basic representation for architects and the construction industry only used paper for building representation and information. The situation has considerably evolved with the emergence of pocket calculators and computers. Since the beginning, scientific results based on computer simulations were simplified and adapted to practitioner's needs, such as tables, diagrams or nomograms, which deliver fast and sufficiently accurate results.

The ancestor of the actual computer-aided design (CAD) tools, Sketchpad, was developed in the early 60's by Sutherland [Sut1963] to draft plans for interior spaces (see Figure 2.1). The idea was to use a graphical interface to directly enter engineering drawings into a computer. The idea was radical at the time, especially when you consider that computers at the time were only batch-processing computers.

Figure 2.1 The console of the Sketchpad Project, MIT, 1963.

The idea of direct interaction with a computer was radical and supported the manipulation of objects using a light-pen, including grabbing objects, moving them, changing size, and using constraints. But this first generation of CAD programmes cloaked their potential efficiency with complexity and slow speed of operation. They managed only geometrical information and could be considered as a digital mapping of the Vitruvius precept.

During the 1970's, the computerised representation of a project evolved to provide a more complex building representation. It did not take long until developments in computer modelling pointed out the advantages of an integrated representation of the building such as described by Eastman [Eas1975]. And also not long to recognise that if geometric information could be integrated, non-geometric information could be integrated as well [Eas1976].

Since the early 80's, the development of communication and information technologies led to a growing awareness of the benefits that could be obtained if isolated programs had the possibility to communicate and exchange information. Barriers to the sharing and exchange of building data between computer applications had to be removed. Various interoperable applications were developed for the construction industry, mainly dedicated to time and cost planning [Lap1997]. Several methods have been developed for a multiple-view simulation of building performance.

2.3 EXISTING APPROACHES FOR MULTIPLE-VIEW SIMULATION

From the viewpoint of simulation capability offered by simulation programs that perform a multiple-view assessment of building performance, four categories have been identified, as detailed in the following paragraphs.

2.3.1 Stand-alone

Stand-alone programs are the most basic solution for a multiple-view simulation. In this approach several *unrelated* applications are used. This obliges the user to create one project model per application as shown in Figure 2.2[2].

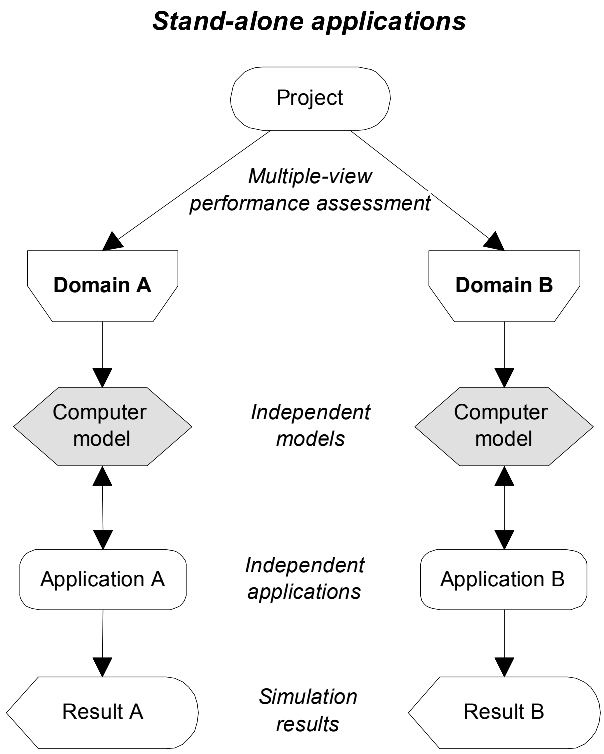


Figure 2.2 Stand-alone approach for multiple-view simulation.

Creating different models of the same project has several disadvantages. It is time consuming. and any modification in the project has to be reported in different aspect models. In practice, a design change must be communicated to each member of the design team, who then must adapt his corresponding part of the model in order to assess the impact on his specific performance domain.
Furthermore, some aspects of different views can require the same input. For example, to support an advanced room acoustic and daylight analysis of a room, a 3D model of the project will be required. If inter-application data transfer is not supported then two distinct geometrical models must be created. The stand-alone approach will then give rise to data redundancy and to potential inconsistency between models. An other limitation of this approach is that the user is required to master each program's interface.

[2] The flowchart symbolism used in this document is defined in Appendix B

2.3.2 Interoperable

Interoperable programs provide a procedure, whereby different computer applications can share or exchange one part or the whole building model. Each program is still used separately and has its own interface. The data model transfer is only possible at the application invocation level of the model, which does not allow an interactive data exchange during the simulation process itself. The following two approaches are possible:

2.A. *Model Exchange*: The stand-alone applications exchange the data model, as a whole or in part, by using a data exchange facility, based on a neutral file format, as shown in Figure 2.3.

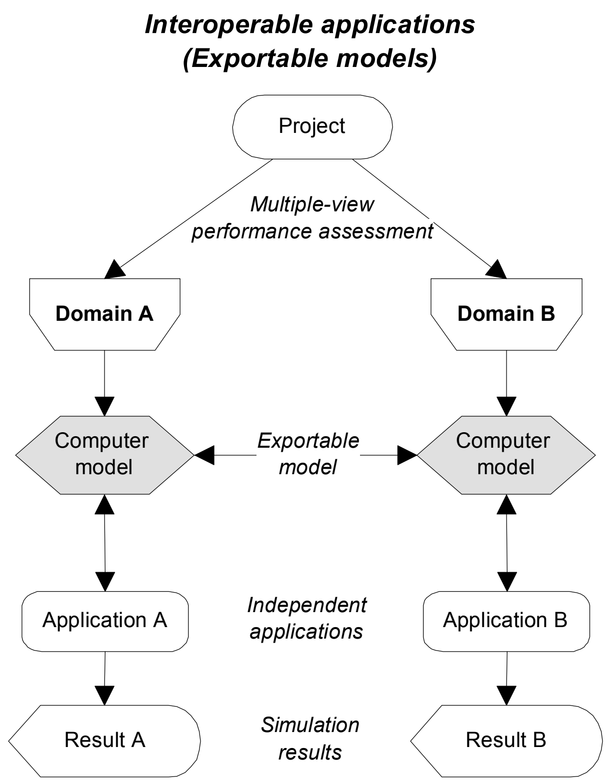


Figure 2.3 Interoperable approach with model exchange for multiple-view simulation.

This exchange of information has the advantage of reducing the time and information required to set up the data model. Unfortunately, when the project is modified, each aspect- model might have to be updated as there is still one model per application, otherwise inconsistency will occur.

2.B. *Model Sharing* : View-specific applications are allowed in this case to extract the data required for their own purpose from a single data management system that holds a single model as shown in Figure 2.4.

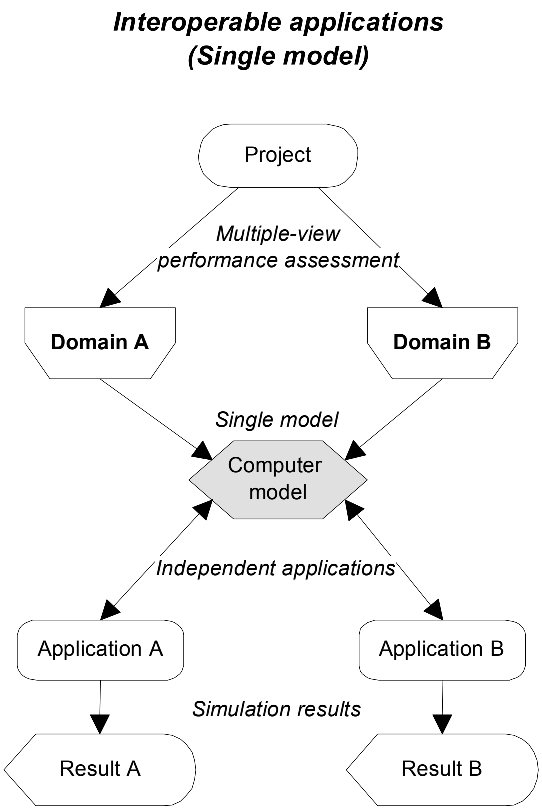


Figure 2.4 Interoperable approach with model sharing for multiple-view simulation

The advantage of sharing a single data model is to centralise the information in order to improve the information availability. It also simplifies model maintenance, but concurrent transactions management is an important and complex issue to solve.

Bazjanak [Baz1997] reports that the transfer of information can account for 80% or more of the resources required to perform a multiple-view assessment of building performance and that the cost of the interoperable approach can be divided by about six compared to the stand-alone approach. The advantage of the interoperable approach is to support information exchange and sharing among partners, which leads to considerable time saving. Among the well-known simulation environments based on the interoperable approach are BDA [Pap1997], COMBINE [Aug1994], ECO-quantum [Mak1997], EQUER / COMFIE [Peu1999], IES-VE [IES1999], RIUSKA [Wri1997], SEMPER [Mah1996b] and UO [Plo1997].

Allowing independent simulation programs to share/exchange data requires a specific data structure that can be used by the different programs, which has led to the definition of standard data models. Several neutral file formats are currently available. For instance, CAD tools generally support DXF [Aut1992] and IGES [IGES1991] neutral format. Although useful, these formats are limited to geometric entities and '*are an electronic version of annotated drawing, lacking in semantic depth*' as reported by Wright [Wri1992]. They do not allow the transfer of physical-related information to downstream applications. Currently, international institutions are working on the development and promotion of standard formats with geometry and physical content, such as STEP [ISO1989] or IFC [Baz1997; Tol1999]. More information about these different formats is given in Appendix C and the next chapter analyses more in detail the possibilities offered by these formats.

Although the interoperable approach may avoid data redundancy, it does not entirely prevent inconsistency and still requires a complex data management system. Furthermore, as with the standalone approach, the user is required to master each program's interface. Finally, it does not allow an interactive data exchange between applications during the simulation process itself. To overturn this weakness, a sequential data exchange can be provided, where the output extracted from one application is used as input in another application. For instance the lighting analysis package ADELINE [Erh1998] can generate an output file of illuminance data, which can be used as input by programs such as DOE-2 [Win1993] or TRNSYS [Bec1994] to perform energy simulation. But when the physics between the views is tightly connected or when accurate simulation is required, the sequential exchange of data may not be applicable any more and a different approach is required.

The interoperable approach can be considered as a computer representation of the real interaction between the partners involved in a project, during which it is not rare that a specific concept has to be controlled by the different partners before its acceptance. This may lead to an iterative process of conception, control and correction as shown in Figure 2.5, which terminates when all parties agree with the final concept.

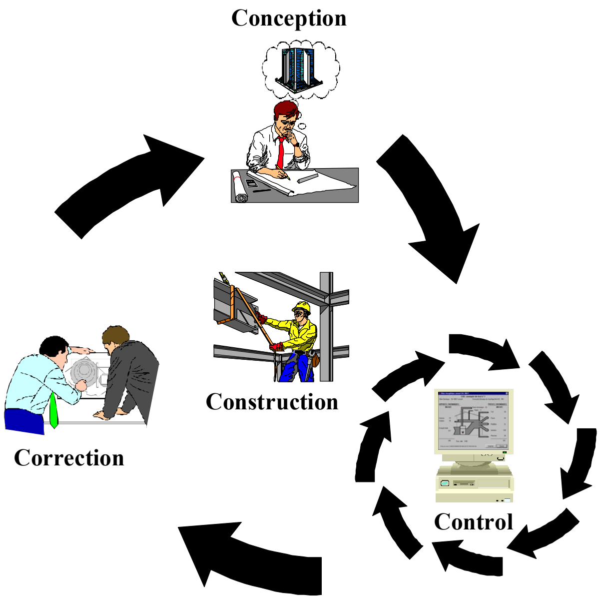


Figure 2.5 The C^4 process (Conception, Control, Correction and Construction). (C4.dsf)

The interoperable approach can be seen as a digital mapping of an inter-partner working process. Within a real project, users would probably recognise that much time and effort is still required for information transactions (locate, translate, exchange, enter and update, check data), even if the interoperable approach may save time. The two following approaches provide a solution in which the computer is used in a more efficient way to simplify the multiple-assessment of the building performance by reducing the user interactions during the control process to the minimum.

2.3.3 Run-time coupling

Coupled (or linked) programs provide the facility to connect applications at run-time in order to exchange information in a co-operative way as shown in Figure 2.6.

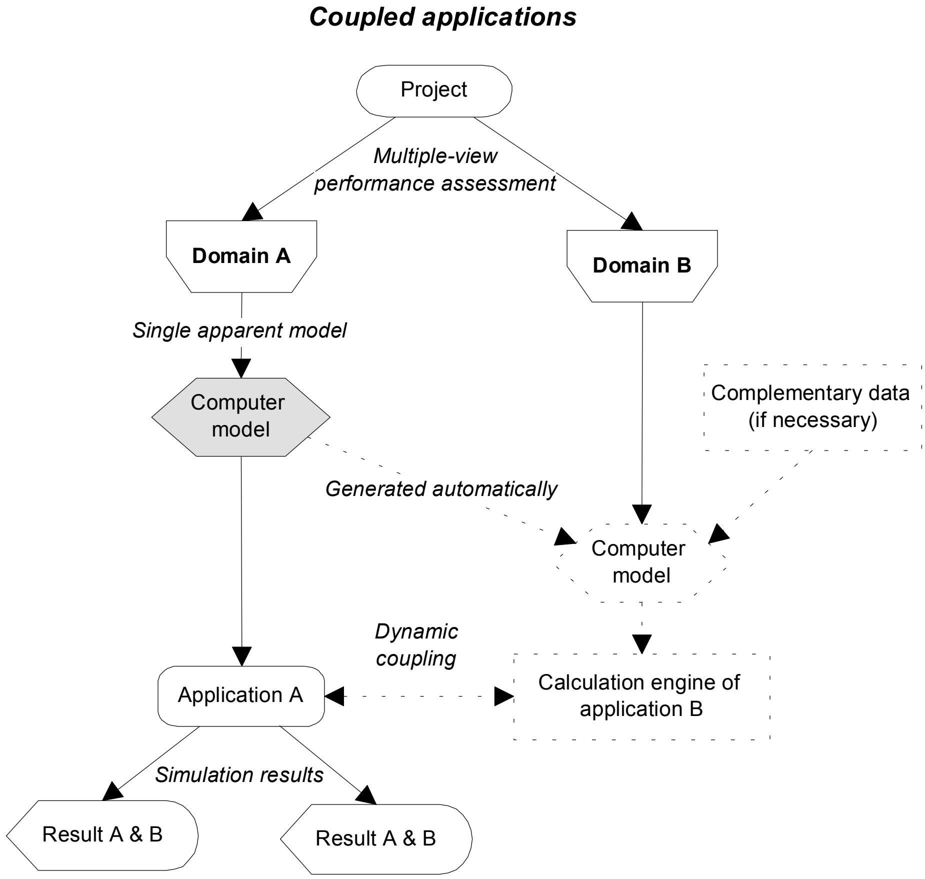


Figure 2.6 Coupled approach for multiple-view simulation.

Generally, one application controls the simulation procedure and requests the other application(s) when necessary. In this case, only the simulation engine of the coupled program(s) is required and the front-end interface corresponds to the driving application. For example, Janak [Jan1998] has enabled a run-time coupling between the thermal/ventilation application ESP-r [Cla1997] and the lighting application Radiance [Lar1993]. Another example of 'ping-pong' coupling has been undertaken between the multi-zone airflow program COMIS [COMIS1998]and the energy program DOE-2 [Win1993].

The main advantage of the coupled approach over the previously described simulation approaches is that it supports the exchange of information during simulation. But the coupled approach, as the interoperable approach, is limited by the maintenance of data and link consistency that depends on the separate evolution of each application.

2.3.4 Integrated

Integrated programs provide a facility to simulate different views within the same program as shown in Figure 2.7.

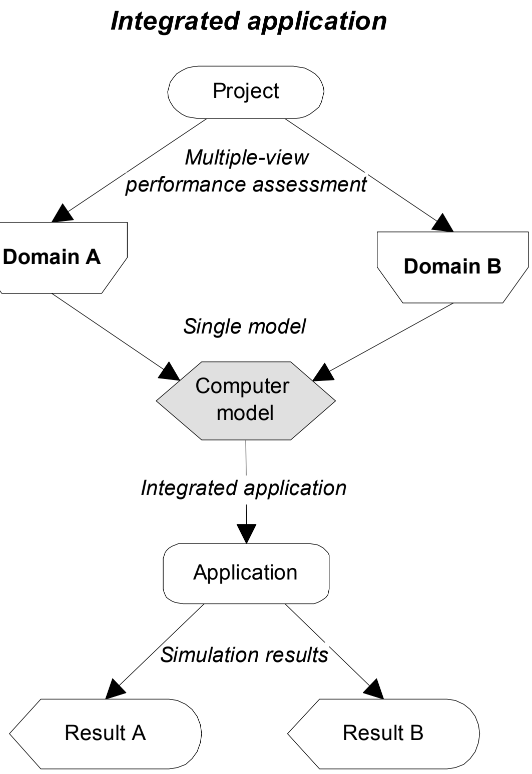


Figure 2.7 Integrated approach in multiple-domain simulation.

As in the run-time coupling approach, a truly integrated simulation relies on the information exchange throughout the simulation to resolve a set of combined equations that represents the driving process of simultaneously occurring physical phenomena. Clarke states [Cla1999] that '*the aim of an integrated approach is to preserve the integrity of the entire building system by simultaneously processing all energy transport paths to a level of detail commensurate with the objectives of the problem to hand*'. It may be important to note, that in the literature the term *integrated* is often used in the sense of *interoperable* as defined above.

Integrated applications can be obtained by extending the capabilities of a single application. Integration can also be achieved by merging into a single tool the best capabilities of existing applications such as done in the case of EnergyPlus [Cra1999] where the energy calculation core of DOE-2 [Win1993] and the ventilation calculation core of BLAST [Bau1983] were merged at the algorithmic level.

Even where domains are not physically interacting, the integrated approach has several advantages. Firstly, the evolution of the application is made easier because it does not depend on external applications. As only one data model is needed to run a multiple-view assessment, data management is simplified. Changes can be made more easily and are better managed; verification becomes simpler, with all data for each element tied together. No exchange file format is required and modifications need only be implemented once. Finally, the fact that there is only one user interface eases the learning process.

Table 2.2 summarises the possibilities offered by the four itemised approaches to a multiple-view assessment of building performance.

Approach	Advantages	Disadvantages
Stand-alone	• Problem specific application	• Several data models • Several user interfaces • No dynamic data exchange
Interoperable	• Single data model • Model consistency	• Several user interfaces • No dynamic data exchange • Transaction management • Complete model if missing data
Run-time coupling	• Single data model • Model consistency • Single user interface • Dynamic data exchange • Physical model	• Link consistency maintenance
Integrated	• Single data model • Single user interface • Dynamic data exchange • Model consistency • Application maintenance	• Require knowledge in various domains

Table 2.2 Comparison of multiple-view assessment methods.

In the author's opinion, only the coupled and the integrated approach can take into account the dynamic behaviour of a building. The efficient development and use of an integrated application requires knowledge of the various views assessed and of constructive principles, as well as expertise in computer simulation. But once the physical model has been created, the integrated approach allows a flexible, simple and powerful multiple-view assessment of building performance.

2.4 AVAILABLE COUPLED OR INTEGRATED SIMULATION PROGRAMS

At present, several programs available on the market support integrated simulation, as summarised in Table 2.3: the assessment of a particular building performance view is graduated depending on the calculation methods used, ranging from 1 (simplified method) to 3 (advanced method). As can be seen, none of the available integrated applications can perform a multiple-assessment of the building intrinsic performance, the occupant comfort and the environmental impacts.

Name	In-built drawing facility	Views							Approach	
		Energy	Ventilation	Equipment (HVAC)	Lighting	Acoustics	Environnemental impact	Comfort†	Coupled	Integrated
BUS++ '97		3	3					I		✓
Bsim2000 (Tsbi5)	✓	3			1				✓	✓
EcoPro		2					3			✓
EnergyPlus		3	3	3	1 or 2			T		✓
ESP-r / Radiance	✓	3	3	3	1,2 or 3			T, V, I	✓	✓
TRNSYS		3	3	3						✓

†Comfort: T = Thermal; V= Visual, I = Indoor air quality ✓: property is included

Table 2.3 Comparison of the features offered by coupled or integrated applications available on the market. Further information on these computer tools is given in Appendix D.

The most appropriate method to take up the challenge of assessing the holistic performance of a building is computer simulation. Currently, the market offers several interoperable programs. The disadvantage of this mode of operation is the complexity of use and its potential for model inconsistency. This can best be overcome by an integrated simulation approach. Currently, there is no simulation program that can estimate energy consumption, comfort conditions and, in parallel, provide the appraisal of the environmental impact of the building throughout its whole life cycle. The remainder of this document details the solution developed to provide a generic approach to a multiple-view assessment.

CHAPTER 3

A DATA MODEL FOR MULTIPLE-VIEW ASSESSMENT

The previous chapter pointed out the importance of assessing the building performance from various views during the design stage and the advantage of using an integrated application to achieve this goal. Such a global analysis requires the establishment of a computer representation of the building that supports multiple-view simulations.

The purpose of this chapter is to present the main assignments for the conceptual representation of a building which is needed as a basis to support multiple-view assessment. The chapter begins by summarising the different representations currently available in the building industry and identifying some limitations to their use in the context of this work. It continues with a description of the basic concepts required by the conceptual building model if it is to support the creation of a multiple-view representation over the whole building life cycle. The key issues to be addressed include geometrical and construction attributes decoupling, life cycle-based decomposition, information completeness, and more general assignments, such as elimination of redundancy, maintenance of consistency as well as application and technology independence. To support multiple-view appraisal, the physical data model should be able to represent a building element for different views at various levels of detail. Furthermore, the data model should be able to adapt to the different phases of the building to enable a life cycle analysis such as of cost or environmental impacts. This chapter concludes with physical properties of the different views that are likely to be simulated for an integrated assessment of the building performance.

3.1 PRODUCT DATA MODEL

The development of a consistent and comprehensive building representation can be schematised in four stages as shown in Figure 3.1. The first step consists in identifying the information required for a comprehensive description of the analysed product. Then the information is translated in the form of a conceptual model, called product data model. A product data model, also named data model, is a high-level and abstract representation of the information structure used to support a suitable digital structure of the information. It includes the complete and non-ambiguous description information about a product in order to facilitate as much as possible its use. This generic definition is applicable to any industrial product, such as a car, a robot or a process. If the product is a building, the term ‘building data model’ is preferred.

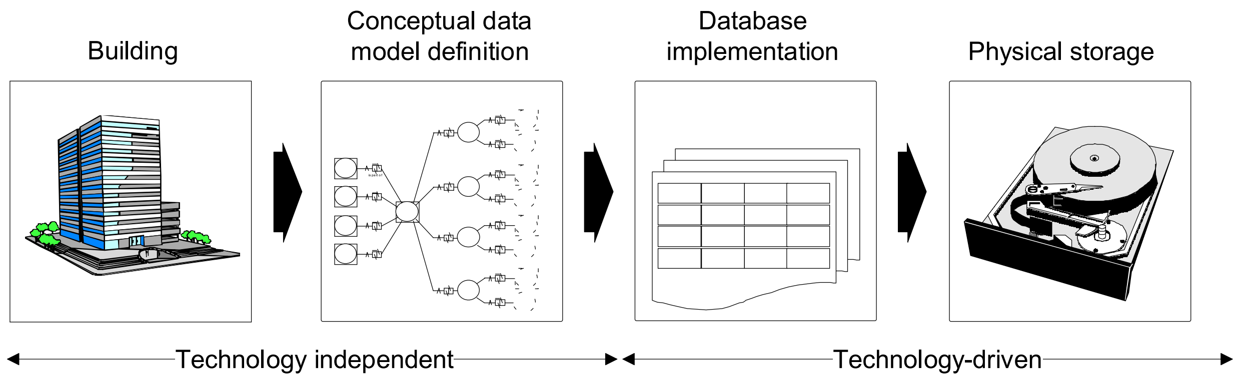


Figure 3.1 Implementation of a building data model. (4 stages of BDM.dsf)

The objective of a building data model (BDM) is to improve the ability to create and maintain a representation of the building and its components at any stage of the development that is consistent, non-redundant and sufficiently complete. It relies on a semantic data language (textual or graphical), which permits an abstract representation of the information structure. Once this semantic representation of the building has been set up, an appropriate technology is selected to implement it in a database management system, which is then physically stored in a computer.

3.2 PRODUCT DATA MODELLING IN THE BUILDING INDUSTRY

Research into building data modelling has been underway since the 1970s [Eas1976; Fen1973]. It has primarily focused on assisting the building industry during the construction process, and has led to software applications such as CAD tools for architects. Unfortunately, the abstract representation defined in a CAD tool, even today, is not suitable for specific engineering applications, mainly because the model does not include any non-geometric information.

During the 80s, several BDMs were released for engineering domains such as structure [Sri1986] or energy [Bou1987], but they were dedicated to a specific corporation. National research projects were also set up to develop more general conceptual models that could be used by the architecture, engineering and construction (AEC) industry, such as those listed in Table 3.1. A comparison analysis between some of these different BDMs can be found in [Bjö1991; Waa1991; Fer1991].

Early BDM	Scope	Origin	Reference
GARM	General AEC model	Delft University & TNO, (The Netherlands)	[Gie1988]
RATAS	Building industry	VTT (Finland)	[Bjö1989]
KBS	Building construction	Swedish Board of Public Building (Sweden)	[Sve1992]
De Waard's model	Building industry	TNO (The Netherlands)	[Waa1992a]

Table 3.1 First generation of data models for the building industry.

Many programs may have used the same data model, but there was a lack of communication capability, which led to the difficulty of sharing the information between different models. Therefore, an analysis of a building from different views led to duplications and redundancies during the data input tasks in the used programs. This was mainly a result of independent developments leading to a lack of agreed definitions for building description and the use of different conceptual approaches in the model schema [Wil1989; Wri1992].

Many concepts and insights had been identified by the first generation of models and were re-worked. The limitations and deficiencies in the existing models gave birth to the Standard for Exchange of Product Data (STEP), developed within the framework of the International Organisation for Standardisation and documented as ISO 10303 [ISO1989]. Its purpose is to provide the capability to represent all product characteristics over the life cycle and create basic conditions for data sharing and exchange among computer applications. This approach has lead to the focus on finding a universally accepted product model that would allow the description of any kind of industrial product. The aim of STEP is to promote neutral means for exchanging information between software applications and its ambition is to cover all aspects of a product during its whole life cycle for all industry domains [Owe1997]. The STEP approach is under constant development in the AEC industry and is also used in domains as various as petrochemistry [POSC1992], robotics [Geb1994] and high-energy physics [Vou1995].

More recently, the International Alliance for Interoperability (IAI) has developed and promoted a new standard data model, called the International Foundation Classes (IFC) [Baz1997]. The IAI is working in parallel to STEP to provide a standard data model restricted to the AEC industry, rather than for all industrial products. More information on standard data models can be found in Appendix C.

During the 1990's, intergovernmental organisations addressed the communication problem between data representation and a second generation of data models, manly based on the STEP approach, was developed with the experience of the previous models. Several important research projects had for assignment the development of a BDM that could be used concurrently by different design tools. The BDMs presented in Table 3.2 focus on the most suitable ways to achieve the data exchange between programs and to provide them with the information required to share a building model. More examples can be found in [CSTB1992; Han1994; Tol1999].

Recent BDM	Scope	Origin	Reference
COMBINE	Building industry	EU-Project	[Loc1994]
CIMsteel	Structural steel frame	EU-Project	[Wat1994]
ATLAS	Building and plant industry	EU-Project	[Poy1994]
OPTIMA	HVAC systems and thermal simulation	EU-Project	[Vol1994]
COMBI	Foundation and structural industry	EU-Project	[Kat1994]

Table 3.2 Second generation of data models for the building industry.

3.3 HINDRANCES OF AVAILABLE DATA MODEL

The development of the data models listed in Table 3.2 has brought forward several hindrances for achieving a comprehensive description of a building during its entire life.

3.3.1 Lack of unified description

Nowadays the STEP approach provides a consistent description of the geometrical information, which is not the case for all aspects of a model. For instance, the material description has not yet obtained a representation consensus. To illustrate the lack of homogeneity of the material description, Table 3.3 shows the physical attributes used in two projects using the STEP methodology. As can be seen, the hygro-thermal attributes are not similar. In addition, the two models do not include attributes for the photo-colourimetry and room acoustics views and therefore, these data models have to be extended to support other views.

View	**Physical attributes**	**CEN N82** [CEN1996c]	**Regener** [REG1997]
Hygro-thermal	Density	✓	✓
	Specific heat	✓	✓
	Conductivity	✓	✓
	Solar absorption	✓	
	Emissivity	✓	✓
	Vapour resistance	✓	✓
Photo-colourimetry	Colourimetry, reflectance		
Room acoustics	Absorption coefficients		

Table 3.3 Physical attributes of the material used in two data models (✓: attribute is included).

The use of the STEP approach, does not necessarily ensure the independence and unequivocal of the model and the data model is not always unequivocal, which may lead to the development of different 'generic' solutions. Arbitrary decisions made during the design of the model could lead to difficulties with providing a BDM to be exchanged, shared and used by several applications. Among projects that use the STEP approach in the building industry can be quoted the European projects COMBINE and ATLAS, which are dedicated to the building and plant industry or OPTIMA for building equipment systems and thermal simulation. Although they embrace the same views, neither the ATLAS nor the COMBINE model met the requirements for the OPTIMA data model [Vol1994]. As summarised by Clarke [Cla1998b], '*although contemporary programs are able to deliver an impressive array of performance assessments, there are many barriers to their routine application, not least the complete absence of standard building product model and any means to manage inter-program transactions*'. Although, these BDMs are very global and powerful, the ensued complexity and the lack of standardisation are a limitation for their acceptance and implementation [Kle1997; Tol1999].

3.3.2 Model integrity

An other key issue is to keep the integrity of the model during complex and concurrent information transactions, which may occur between different applications when several users work simultaneously on the same building model (interoperable approach on the sense of Chapter 2. Various transaction management systems have been proposed such as in COMBINE [Cla1995a], COMBI [Kat1994] or INTOX [Mor1993]. They tend to support concurrent transactions and preserving the audit trail (who did what, when and why), based on a central "blackboard" used for handling of the communication between application(s) and user(s), and the management and traceability of the information flow.

Grau [Gra1999], who took part of the *COMBINE* project, admits that '*although these projects succeeded in developing and demonstrating the functionality of the interoperability in building design systems, it was clear that such comprehensive systems face a problem with complexity, which influences the required effort for development work as well as the efficiency of using the final system.*'. And Galle [Gal1995] adds that concurrent transactions management and semantic integrity maintenance may not be achieved simultaneously, which is a limitation to the interoperable approach.

Another important issue of a BDM is related to data redundancy. Although it may sometimes not be eliminated in complex data models [Vol1994], it would be preferable to avoid data redundancy for several reasons. First, it increases the size and the complexity of the BDM, even if for current computers, this is not a major limitation. Second, when a data is redundant, its modification requires finding and updating all data instances to keep the BDM consistency, which may complicate the BDM structure. When data is stored in one place only this management process is performed only once.

The multiple-view assessment proposed in this work attempts to develop a single simulation program were no exchange or sharing of the BDM (or part of it) between different applications is requisite. The BDM developed here places the information required by different views (integration) at the disposal of a single application rather than it being shared by different applications (interoperability). The information required by each view is extracted sequentially from the BDM, and therefore does not require the development of a system to manage concurrent transactions. The consistency of the model is automatically guaranteed.

3.3.3 Life cycle representation

Another key issue for a multiple-view BDM is to support life cycle analysis. Currently, many of the developed data models have either been developed for a specific stage or a few stages of the project life cycle [Far1999]. Even the information systems for data exchange and management available in the international arena, such as STEP and IAI, are unsuitable to allow the design life of buildings process to be carried out [Bur1998].

Even though a considerable effort has been undertaken to develop a standard data model for the building industry, it seems that no standard model has yet been achieved for the building industry. Clearly, the global assessment by means of an integrated application of building performance, occupant comfort and environmental impacts generated during the building life could not been achieved with existing building data models.

3.4 GENERAL REQUIREMENTS FOR AN INTEGRATED PRODUCT DATA MODEL

The developments undertaken in this work are dedicated to the elaboration of an integrated application, in the sense developed in the previous chapter, i.e. in a single simulation application, which does not require information sharing or exchange with other applications and enables the multiple-view assessment of building performance. The BDM developed in this work relies on the following principles**:**

- **Decoupling of the geometrical and construction[3] attributes**: the geometrical representation of a building element does not give any information on the corresponding material used within a construction. This entails the building geometry to be independent of its construction properties and both representations to be decoupled.

- **Life cycle-based decomposition**: to enable the management of attributes associated with a life cycle assessment, the data model associated to the physical properties supports a structure that results from the decomposition of the building life into elementary life cycle phases.

- **Multiple-view decomposition**: to enable a multiple-view assessment of building performance, a comprehensive set of attributes is retained for each possible view.

Before detailing these main principles any further, some general characteristics must be defined, that are: (1) The approach used to define the model and (2) the boundary limits of the model. Once these general requirements have been defined, the particularities of the BDM proposed here are scrutinised in a second step.

3.4.1 Problem-driven approach

The question addressed in the design of a BDM could be: ‘Which applications or technology can be used to perform a multiple-domain assessment of building performance?’. The answer to this question would lead to a ‘technology-driven’ solution, which attempts to explore the possibilities offered by a technology to resolve a particular problem within its own domain. The second solution, adopted in this work, is to use a ‘problem-driven’ (also named bottom-up) approach, which addresses the problems to be solved before considering how the data model might best be implemented. Its aim is to take the problem to resolve as the point of departure of the research, and to develop the corresponding data model. The BDM should be able to be implemented on any platform using any programming techniques. No technology-related concessions should have to be made in the structure definition of the BDM before its implementation.

Thus the question addressed in BDM design should be ‘What information is required for an integrated assessment of building performance ?’ Once this question has been answered, the ‘problem-driven’ approach seeks for the most appropriate technology to implement the concept in a computer environment.

[3] The term construction is equivalent to a multi-layer composite, i.e. is the materialisation of an element.

3.4.2 Universe of discourse

A data model allows to communicate information related to a certain part of the real world or abstract world, which is called the universe of discourse (UoD). Recent efforts have been channelled into defining comprehensive data models for the whole AEC industry, which leads to difficulties when put in practice. The attempt of STEP is to provide a comprehensive BDM for the AEC industry, but '*"completeness" is only possible for a closed system and it is always possible to find applications which require data which are not contained within such a comprehensive and global product model*' as reported by Wright [Wri1992]. There will always be special requests within the data model, which cannot be known at the time of definition of the model and may lead to a never-ending development.

It may be more convenient to restrict the data model to a more specific purpose. Using a comprehensive model for buildings, when unnecessary, can lead to insurmountable problems of data. Restricting the UoD allows simplifications, which entail a better understanding of the model and simplify its implementation in practice. One major advantage of using a restricted data model is that the integration model does not have to fulfil the high standard of the general data model for the whole AEC industry [Tol1999].

The UoD of the proposed BDM does not have the pretension of providing the solution for the whole AEC industry. It is restricted to the information required to ensure the assessment of building performance (energy consumption, room acoustics, lighting, etc.), occupant comfort (thermal, visual) and the environmental impacts generated by the building during its whole life.

3.5 DECOUPLING THE GEOMETRICAL AND THE CONSTRUCTION ATTRIBUTES

Most existing data models combine geometrical and non-geometrical information into one entity, as for example in the European Committee for Standardisation (CEN) data model [CEN1996c]. At the construction level and at layer level, the CEN model simultaneously holds geometrical and physical attributes as shown in Figure 3.2. The construction is described with its area and U-value attributes, which are required, for instance, by the CEN method [CEN1998] to perform a steady-state energy balance. The advantage of this approach is to limit the input attributes to those required for a particular view.

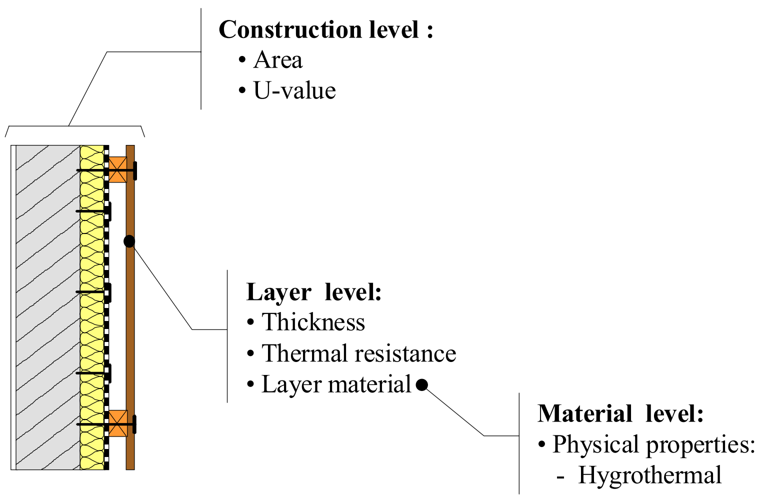


Figure 3.2 Schematic data model of a construction proposed by the CEN organisation in [CEN1996b]. (CEN vs Mine2.dsf)

Although easy-to-use, this approach reduces the flexibility of the data modification. When a physical attribute of a construction type is to be changed within the building, the corresponding physical attribute has to be changed in any building element made of that construction. This process requires the localisation of each instantiation of the corresponding element and the update of the physical attribute.

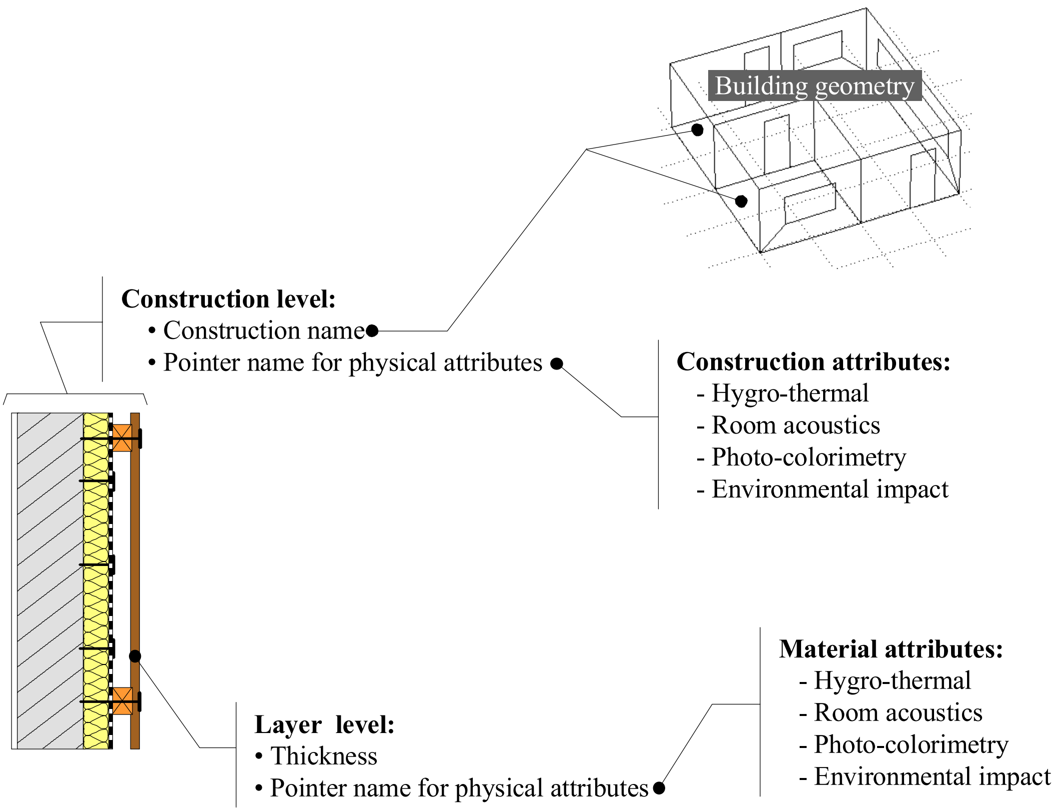


Figure 3.3 Abstract representation of the separation between geometry and physical model.

(CEN vs Mine2.dsf)

From a general point of view, the geometrical representation of a building element does not give any information on the corresponding material properties. For instance, an internal partition can, a priori, be of any kind of construction. This enables the element geometry to be independent of its construction materialisation: the same material can be used by various building elements. To keep the flexibility of the model representation, the geometry can be decoupled from the construction properties. The information required to create a computer representation of a building can be separated into the two following categories:

- *Geometrical* attributes, which holds for instance the dimension, the orientation, and the functionality information.

- *Construction* attributes, which holds the attributes of the corresponding construction material(s), such as the material density and environmental impacts.

Both models are independent and are linked by a common attribute that connects the geometry of a building constituent to its physical representation as shown in Figure 3.3. In this approach, there is a many-to-one relationship between the building geometry and the construction model, i.e. one construction type can be used by several building elements. Data management is therefore simplified and there is a reduced volume of information, compared to a solution where both models are merged, as shown in Figure 3.4.

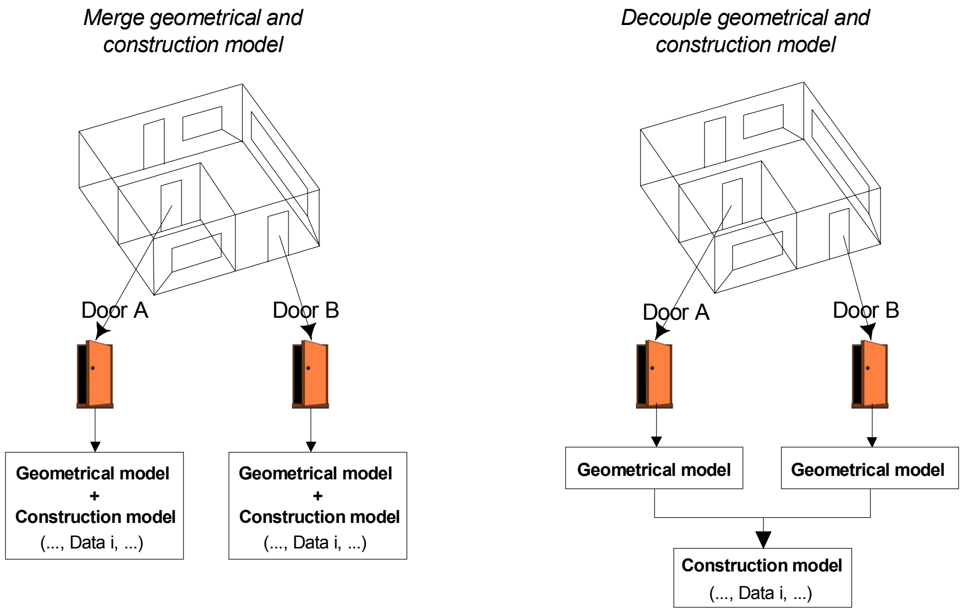


Figure 3.4 Information required for a geometry-physical merged model (left) and a geometry-physical decoupled data model.

Separating the geometrical data model and the physical data model has several advantages in terms of data consistency and model extensibility. If the physical and geometrical models are merged, maintenance becomes more complex. For example, to update the value of a physical property, it is necessary to find each occurrence of that property in the model, which can be a time consuming process in cases where the data model is large. Separating the geometry and physical model eases the maintenance and consistency of the building model in the sense that the physical information related to a material or a construction is stored in only one place. Therefore any modification of a property also needs to be performed only once.

The geometry required within an application depends on the view to assess, the level of detail of the problem to resolve, and the calculation method(s) used. This may lead to many different geometrical representations of a building element. For instance, a one-dimensional representation may be sufficient for the steady state assessment of the hygro-thermal performance of a construction, while an advanced lighting simulation would require a three-dimensional geometry model.

3.6 CONSTRUCTION DATA MODEL STRUCTURE

A construction is made of several materials, whose representation might differ depending on the analysed view. For a construction, as the one shown at the top of Figure 3.5, only the photo-colourimetry attributes of the inward material are required for a lighting performance assessment, while for a life cycle impact assessment, the environmental attributes of all constituent materials must be taken into account. To support a multiple-view assessment, the data model of the construction should therefore be able to fit each view representation and must include all the necessary attributes required by all possible views.

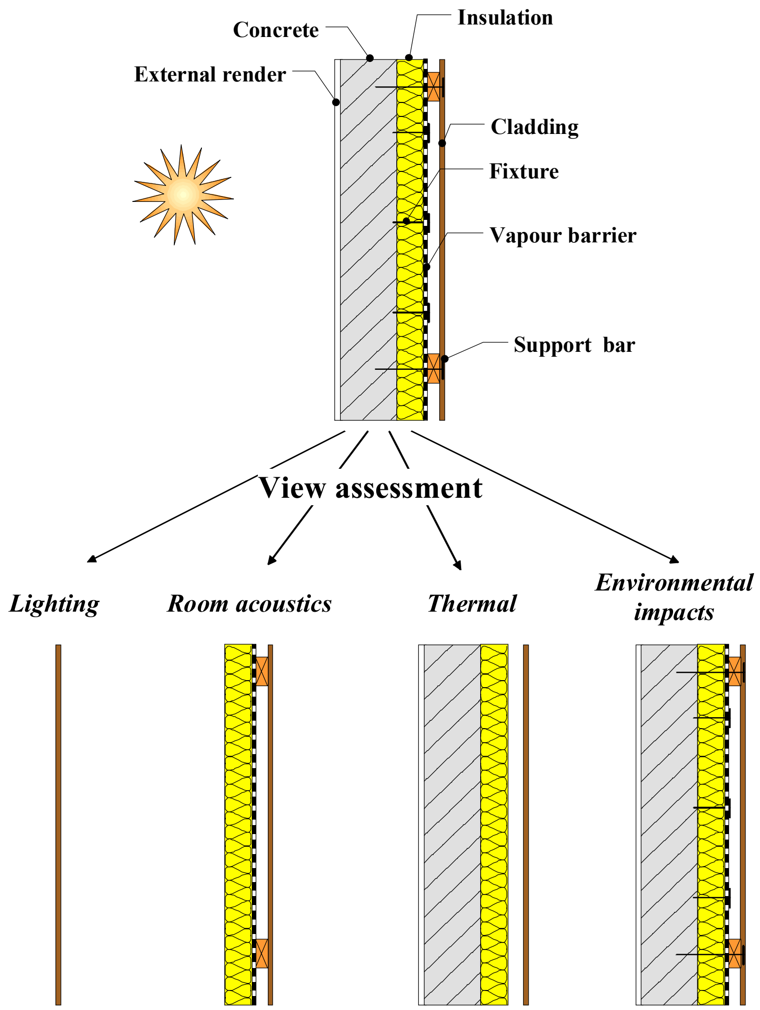


Figure 3.5 The construction representation may differ depending on the assessed view. (mlc.dsf)

For a particular view, assessment methods can be ranked from simple to detailed. Methods in the latter category will typically require a detailed description of the materials comprising a building component, while methods in the former category will typically require only global properties such as U-value. During the design stage, this level of detail is volatile, with the level of descriptive detail growing as the design evolves. In order to include the physical properties related to the material and, at the same time, the physical properties related to the whole construction, the physical data model should allow several levels of abstraction. For a specific domain, the physical properties can be expressed at the material level and at the construction level. This scheme has three advantages.

Firstly, it enables the physical data model to be used with calculation methods that use *different levels of abstraction*. For example, the photo-colourimetry attributes of a construction are equal to the photo-colourimetry attributes of the material at the construction surface. Unlike the photo-colourimetry attributes, the room acoustics attributes of the construction are not necessarily equal to the attributes of the external materials, but may depend on the construction composition. For instance, Figure 3.6 shows the effect of the construction composition on the absorption coefficients of two constructions, one made of a wood cladding directly on the concrete and the other one with an air gap between the two materials. As can be seen, the absorption coefficients are unchanged for both constructions when the sound strikes the construction from the concrete side (② in Figure 3.6). In this case, the set of coefficients of the construction is equal to the set of coefficients of the concrete. The behaviour is different when the sound strikes the construction from the cladding side. As can be seen, the air gap influences the absorption of the construction. If the cladding is directly placed on the concrete (③), the set of absorption coefficients is the same as for a massive piece of wood, i.e. the outer material. When the cladding is shifted from the concrete (①), the construction absorbs sound at low frequency thanks to the air gap located behind the cladding. Therefore, for views such as room acoustics, the physical attributes are required at the material- and at construction level

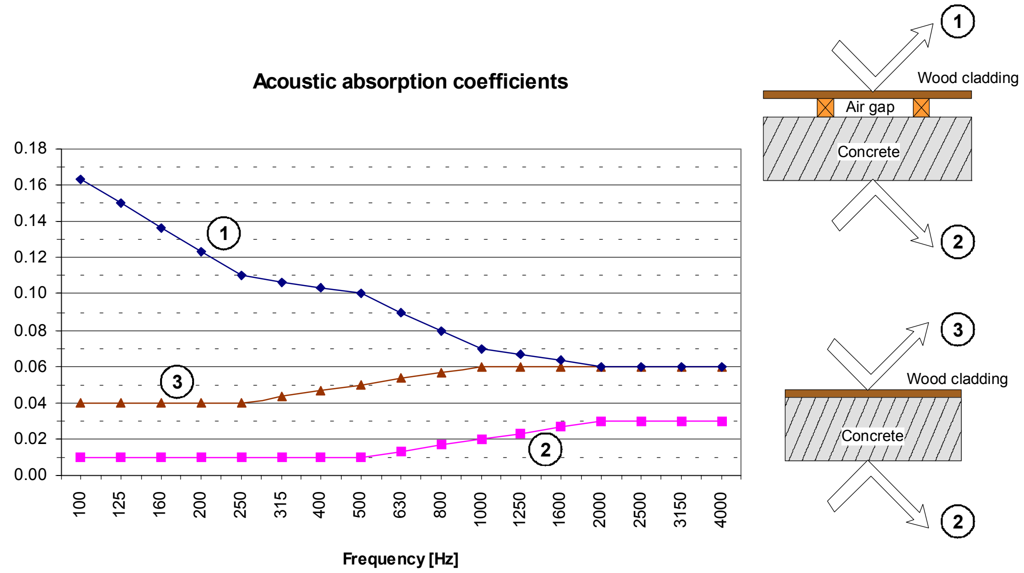


Figure 3.6 Effect of the construction composition on the acoustic absorption coefficients. (Acoustic vs colour2.dsf)

The second advantage of a variable level of abstraction is to allow the establishment of a model that at the same time includes *different levels of resolution*. If the performance assessment has to focus on a particular part of the building or building element, this part can be represented at a high level of detail, with the remaining parts represented at a lower level of resolution. For example, a particular building facade can be assessed in detail by representing it at the material level, while the remaining facades can be subjected to a rudimentary treatment using data at the construction level. The project description may therefore be heterogeneous in terms of resolution.

Thirdly, multiple levels of abstraction permit *concurrent treatment* of material and construction level information. The performance of a building element can therefore be assessed globally by including the influence of its constituent materials and factors relating only to the whole construction. For example, the environmental impact of a window depends not only on the impacts of each comprising elements (material level), but also on the window assembly and transportation processes (construction level). In this case, material and construction information is necessary at the same time. To summarise, allowing different levels of abstraction for the same building component enables the data model to be used with various assessment methods. Even so, the data model will not be method independent: to achieve this, the data model must be extended as described in the following section.

3.7 REQUIREMENTS FOR A LIFE-CYCLE BASED STRUCTURE

The previous sections proposed a physical data model that enables a comprehensive representation of building elements at various levels of resolution and includes sufficient information to make it calculation method independent. But it does not include information related to the building's life cycle. In other words, the model is applicable to assessment methods that do not support segmented life cycle analyses. The semantic of the data model should be generic enough to take into account the various elements and processes used during the building life span. And to be able to undertake a life cycle impact assessment, it is necessary to associate the physical attributes related to the different parts of the construction with the corresponding life cycle phase.

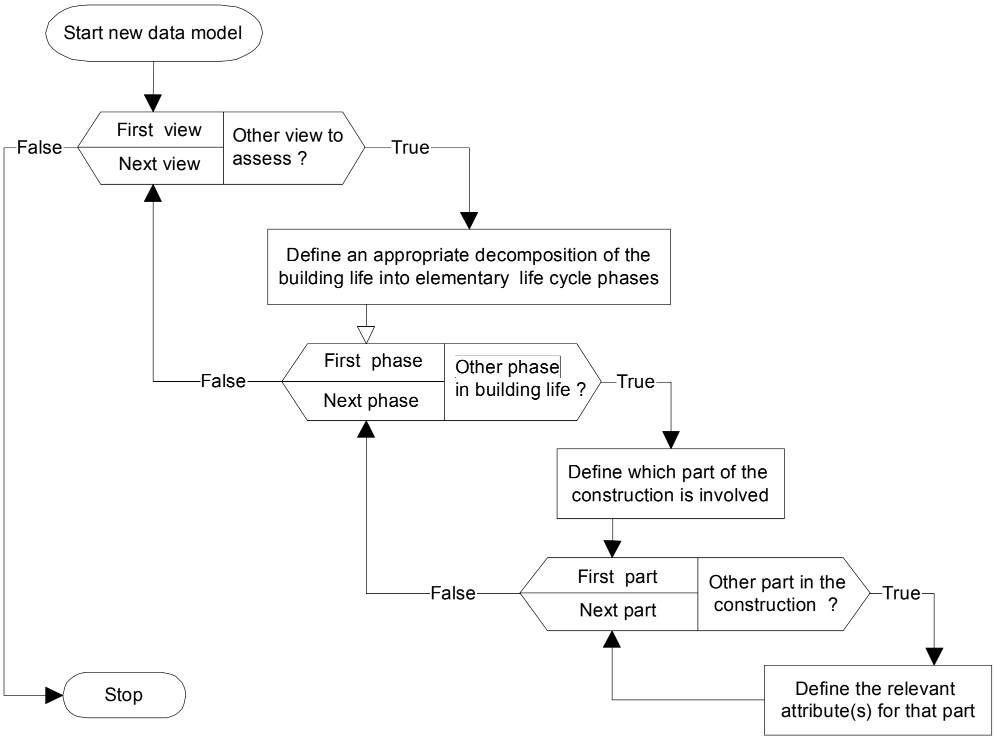


Figure 3.7 Iterative method for the definition of the physical properties according to the relevant life cycle phases, views and construction parts. (Specific data model construction procedure.flo)

Figure 3.7 presents an iterative method for the definition of the attributes to be included in a construction data model that takes into account the life cycle phases decomposition, the construction part involved and the physical attributes of the building element. This method is divided into the following steps:

1. Decompose the construction representation into relevant views.
   2. Decompose a view into relevant building life cycle phases.
      3. Define a part of the construction that is involved during that life cycle phase (construction- or material-level).
         4. Define the relevant physical attributes.
      5. Iterate from Step 3 for each construction part.
   6. Iterate from Step 2 for each construction part.
7. Iterate from Step 1 for each elementary phase.

For each view, the data model is subdivided into the relevant life cycle phases, which correspond to that particular view. Then, for each phase, the corresponding physical properties are incorporated into the construction data model either at the construction or material level. If a view covers more than one life cycle phase, then each relevant phase holds the physical attributes corresponding to the considered view. For example, the environmental impacts generated by the material fabrication is related to the manufacturing phase, while the impact generated by the material waste management is related to the disposal phase, and so on.
With the use of the above iterative method, the specialisation of the construction data model is limited to the definition of the view to be included in the model. Due to the configuration, any modification at the view level does not affect the remainder of the model structure. Views can be added, modified or removed without affecting the lower levels of the construction data model. The more view it includes, the more multiple-domain assessments can be performed.

3.8 LIFE CYCLE PHASES DECOMPOSITION

To achieve a consistent BDM, the building life must be divided into elementary phases to enable a rigorous life cycle analysis. Especially, it must be capable of taking into account the management of maintenance and replacement schedules for different building elements as already discussed in a previous paragraph. The decomposition of the building life into elementary phases should be in line with standard building life cycle representation. Not too detailed to avoid a lack of information availability, but sufficiently elaborate to allow a state-of-art life cycle assessment.

A first possible life cycle decomposition may comprise the construction phase, the utilisation phase and the decommissioning, such as proposed in [BRB1985]. Although possible, this simple segmentation of the building life is not sufficiently elaborate to permit a detailed analysis of the life cycle cost (environmental, financial, etc.) performance of a building and it is necessary to sub-divide this structure into more elementary phases. Table 3.4 presents the retained decomposition of the building life based on different life cycle phases decompositions proposed in various sources, related to different domains of the building industry, as detailed in the Appendix E.

Major phases	Elementary phases	Related to
Material manufacturing	• Material manufacture (includes, raw material extraction, process and transport)	Material
Building construction	• Transport to construction site	Material
	• Construction assembly	Material
	• Transport to building site (prefabricated)	Construction
	• Placement on building (prefabricated)	Construction
Building use	• Operation	Building
	• Maintenance	Construction
	• Replacement	Material
Building elimination	• Deconstruction	Material
	• Transport to disposal site	Material
	• Disposal management	Material

Table 3.4 Decomposition of the building life cycle into elementary phases.

The life cycle phases upstream to the *Building construction* have not been explicitly included in the decomposition proposed in Table 3.4. They correspond to the extraction of raw materials, their processing and the transport required to manufacture a construction material. These phases are instead merged into the *material manufacturing* phase for the following reasons. Firstly, the number of raw materials that may comprise a material, and the number of processes required to manufacture that material, could be considerable. Even if it were not limited by computer computational power, it would be difficult to locate and keep this information up to date. Secondly, the industry evolves constantly in terms of the raw materials used, their origin and the processes employed in manufacturing. The lack of data would have an impact on the consistency of the information. For these reasons, aggregated data covering the phases from raw materials extraction up to the manufacture of the final component are used. Therefore the data model does not require a more extensive decomposition of the building life cycle. Aggregating these phases is not a limitation of the proposed method, but a phase restriction at the implementation level.

In the Table 3.4, the *construction site* is defined as the location where the materials are worked-up to erect a construction, i.e. where the materials are assembled into a building element. For most of the construction materials, the construction site corresponds to the building site. But for materials that compose a prefabricated element such as a glass pane, frame or spacer, the construction site corresponds to the pre-fabrication factory. This lead to the following definition of the construction site:

$$\text{Construction site} = \begin{cases} \text{Prefabrication site,} & \text{if prefabricated element} \\ \text{Building site,} & \text{otherwise} \end{cases}$$

After assembly, the prefabricated element is transported from the construction site to the building site. This latest transport does not exist for non-prefabricated element. For more explication and for a detailed description of each phase's limit, the interested reader can refer to Appendix E.

The proposed life cycle phase decomposition can be perceived as a backbone in which the vertebras correspond to the different life cycle phases. For each phase, the relevant views involved are identified and for each view, the physical attributes requisite for the different calculation methods are determined.

3.9 VIEWS DECOMPOSITION

An important issue in the holistic assessment is to determine the views that will impact on the performance issue to be addressed. It is well accepted that energy related indicators, such as energy consumption are insufficient for building performance characterisation. Improving the occupant well fare through a suitable indoor environment quality may lead to an improvement of productivity in offices and health cost reductions [Sen1998]. The occupants' well fare is a combination of occupant comfort, related to the environmental stimuli (air temperature, illuminance, etc.) and affective factors, such as the working ambience and familial environment. The latter factors are specific to each person and cannot be appraised during the design phase of a building and are nor considered below.

Occupant comfort is mostly assessed in psychophysical investigations that seek to establish a measurement scale of the psychological experiment of an environmental stimulus and to relate the response to a scale of measurement of the stimulus. In practice, occupants are generally exposed simultaneously to a combination of physical stimuli. Because of the human body's complexity, the occupants' sensational responses are generally not only driven by one environmental stimulus.

The occupant thermal comfort is also an important issue that has to be included. For instance, Fanger [Fan1970] has introduced a thermal comfort model that takes into account several environmental stimuli, such as air temperature or occupant activity and clothing. Discomfort glare is another important aspect of occupant comfort. Guth, among others, [Gut1963] has developed a model that quantifies the visual comfort probability for a certain task under certain lighting conditions.

A modification of one or several stimuli will affect the comfort of the occupant and thus affect his perception of the other stimuli. Several studies [Clau1993; Hor1985; Sen1993; Wyo1993] have demonstrated that occupant comfort is the global and simultaneous response to external stimuli exposure (thermal, lighting and acoustic) and asserted that a multiple-domain comfort assessment is required. Yamazaki [Yam1998] suggests that workplace suitability requires higher illuminance levels when sound pressure increases. Occupant comfort should not be regarded as a response to a unique stimulus but as a global psychological reaction to any environmental stressors. The concept of an acceptable *level of exposure* for a particular comfort view, such as the required illuminance level or operative temperature at the work place, depends not only on the considered domain but also on the whole environment in which the occupant is swathed. This demonstrates the importance of providing an integrated approach, which could concurrently assess all connected comfort aspects.

Although it was not considered in the references mentioned above, the air quality is also an important factor that affects the occupant's comfort. The concern of reducing the energy consumption has led to a reduction of air leakage through the building facade, which may reduce the renewal of fresh air and could be compensated by the use of mechanical ventilation. This antinomy between energy saving and air quality has an important impact on building performance and occupant comfort, which must be appraised at the design stage of the building. According to the previous considerations, thermal, acoustic, air quality and lighting can be regarded as primary environmental stressors, which affect the indoor environment quality.

The analysis of the overall performance of a building should not only take into account building performance and occupant comfort, but also the ecological cost of providing them. The analysis of the overall performance of a building should also take into account the ecological cost of providing this comfort. Although nowadays there are not yet 'green' standards, the environmental impacts of a building during its life span can be estimated, and should be included as a new view requiring performance assessment.
In the light of the previous sections, the holistic appraisal of *building performance* should focus on the following domains:

- *Intrinsic building performance* such as energy consumption and room acoustics
- *Occupant comfort* including thermal and visual comfort
- *Environmental impact assessment* generated during the building life span

Except for the environmental impact assessment, the views are related to the operation of the building and the corresponding data are therefore connected to this particular life-cycle phase, as shown in Figure 3.8. Some phases are related only to the material, some are related to the whole construction, while others are related to both. For example, the environmental information related to the construction of a window (pre-fabricated element) includes the manufacture of the constituent elements (panes, frame, etc.), which are material related. The placement of the pre-fabricated window on the building is related to the whole construction. For the phases related only to the material, the corresponding information is independent of its use within a construction. More generally, the information at material-level can be considered to be invariant and is therefore project independent. While information at construction-level is construction dependent and therefore cannot be defined before the building element has been defined. This construction information is then project related.

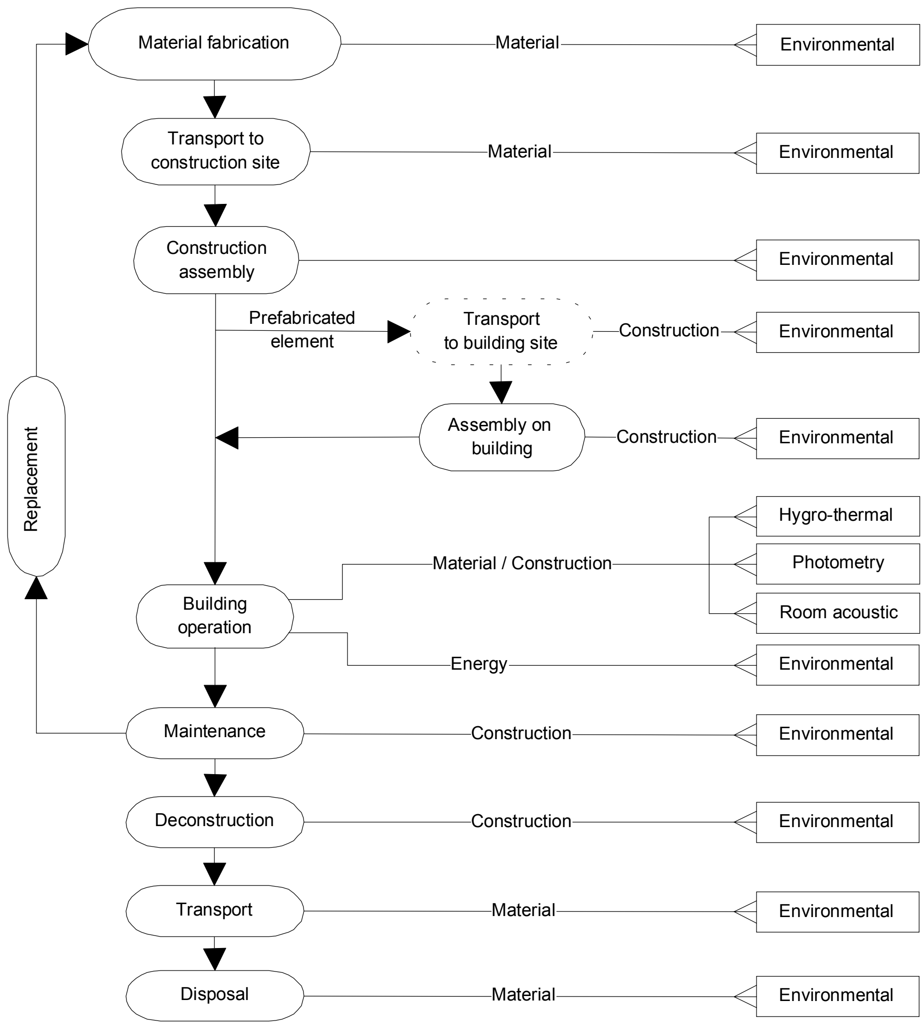


Figure 3.8 Physical data model based on the life cycle approach to perform an integrated assessment of building performance. (Material life-cycle vs performances variante 1 (très-petit).flo)

This chapter has developed the assignments of the construction data model that can support multiple-view performance (energy, ventilation, lighting, etc.), occupant comfort and environment impacts assessment. In establishing this model, no application-related concessions were made, to keep its technology independence. The construction data model is based on a decoupling between the geometrical description of a building element and its construction materialisation. The construction data model is decomposed by view, each of them holding a comprehensive set of physical attributes, in order to become assessment method independent. In order to support the description of all the processes associated to the building's life, the part of the construction data model associated with the life cycle impact assessment includes a decomposition of the building life into elementary phases, from cradle to grave. The next chapter presents how this structure has been implemented in an existing simulation program and which physical attributes have been retained for each selected view.

CHAPTER 4

IMPLEMENTATION IN AN EXISTING BUILDING SIMULATION PROGRAM

The previous chapter identified the requirements of a physical data model that supports a comprehensive representation of building elements with sufficient information for a multiple-view assessment. The proposed approach could be implemented in the form of a new integrated application that enables a holistic assessment of building performance. However, within the time schedule of this work, it would not have been feasible to develop a new integrated program starting from scratch. It was therefore preferred to select an existing building simulation program in which the data model was implemented and whose functionality was extended to support the assessment of the missing views. This solution permits examining the capabilities of the proposed approach to map and enlarge the assessed views in an existing application.

This chapter starts with the selection of an existing simulation program and summarises its structure, especially its geometry model. It continues with a detailed description of the data model that holds the physical attributes of materials. Then an appropriate technology is selected to implement the management of the physical information in a database manager. The chapter ends with the description of the solution retained to assist the retrieving of information from the database.

4.1 SELECTION PROCEDURE

The building simulation market offers powerful building simulation programs (BSP) that perform multiple-view assessment. Unfortunately, none of the available tools can perform a coupled or - even better - an integrated appraisal of all the major building performance indicators (energy, lighting, ventilation, room acoustics), occupant comfort and environmental impacts as shown in Table 2.3. The implementation of the proposed solution required the selection of an existing BSP and its extension to support the assessment of the missing view(s).

Among the selection criteria, hardware requirements were not considered as relevant. Desktop computer evolution, CPU speed and disk-storage capacity increase at an exponential rate, while at the same time the cost decreases. On the operating system (OS) side, BSPs generally run under UNIX®, WINDOWS® or the emerging GNU/LINUX® system, which can be obtained at a reasonable cost. Hardware and OS's are consequently no longer restrictive arguments that can limit the selection of a BSP. The user skills related to OS use and the application learning process can be

an important issue as developed by Hand [Han1998]. These issues have not been considered because the selection criteria are related to the simulation capabilities of advanced simulation programs rather than user capabilities. According to the approach advocated in this work, the selected BSP should be based on an integrated approach and must provide a 3D representation of the project. It should also include the current state-of-the-art in building simulation, should be recognised in the scientific community, must still be under sustained development and should support an open architecture, in order to offer free access to the necessary source code.
Only existing capabilities have been considered and the selection is based on an extensive analysis on existing BSPs, for which information was extracted from literature review, Web sites, testing full or demo versions, personal correspondence with developers, and personal experience in building simulation. Among other sources, reviews on BSPs inter-comparison can be found for instance in [Att1996; Gou1999; Hal1999; Hon2000].

4.2 ESP-R FUNCTIONALITY

As a result of the selection procedure, ESP-r (Environmental Systems Performance, r stands for 'research' version) was chosen. It is a transient energy simulation system, capable of modelling energy and fluid flows within combined building and plant systems. ESP-r has been under sustained evolution since 1974 and is currently developed by the Energy Systems Research Unit (ESRU) team at the Strathclyde University in Glasgow [Cla1977].

ESP-r was selected because of its flexible and modular structure that facilitates the development and implementation of new views and for its advanced modelling capabilities that include complex physical processes such as the ones described below.

- Transient heat transfer through opaque and transparent multiple-layer construction, using a nodal network based on hourly or smaller time steps .
- Multi-zone airflow can be calculated using constant rate or advanced methods, such as a nodal network [Hen1991] and CFD [Neg1995].
- Heat transfer calculation includes radiation, convection and conduction transfer through construction with a time variable surface convection coefficient.
- Several HVAC systems with common control strategies can be explicitly modelled using a transient approach [Aas1993]
- Transparent units are explicitly represented as a multiple-layered construction and include obstruction shading effects.
- Long-wave radiation exchange is accounted on a time-step basis with a radiosity-based approach.
- Artificial lighting can be dynamically controlled using common control systems and strategies depending on time schedule or indoor daylight illuminance [Jan1998].
- Extensive energy management control systems are implemented [Mac1997]
- Detailed simulation of the electrical power circuits is supported [Kel1999]
- Assessing uncertainty impact on simulation results is available [Mac1999]

* Supporting special components simulation, such as that of transparent insulation material (TIM), photovoltaic panels, advanced glazing systems and renewable technologies.
* Several model converters have been implemented in ESP-r to support the transaction of the geometry information with CAD tools.

ESP-r is firstly dedicated to those who have practical knowledge in building simulation, such as researchers or competent consultants. It is used in many international projects, such as COMBINE [Cla1995a], Daylight-Europe [Sca1997a] and IMAGE [Cit1999b]. Appendix F gives a brief user guide of ESP-r and more information can be obtained on the ESRU web site (http://www.esru.strath.ac.uk/ESP-r.htm), which includes, a description of the system, simulation theory, published papers, a review of example models, a self-learning course, etc.

4.3 ESP-R STRUCTURE

In ESP-r, a system level manager, called *Project Manager* (PM) controls the entire project design and simulation tasks, as shown in Figure 4.1.

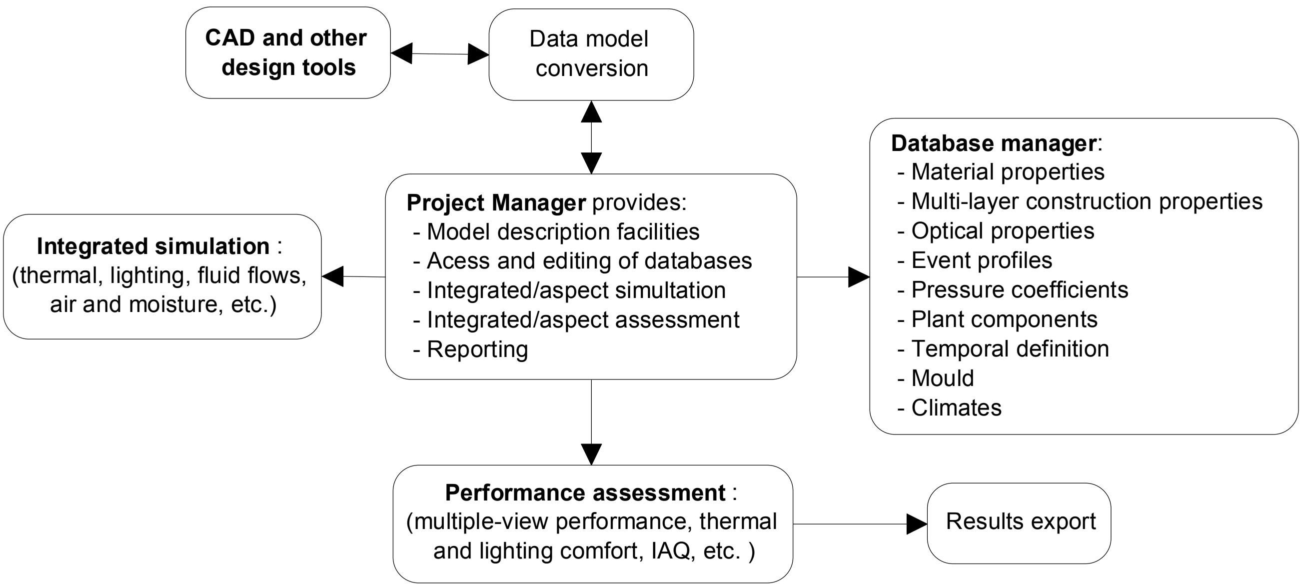


Figure 4.1 ESP-r structure and functionality. (ESP-r suite.flo)

The PM allows the importation of an external CAD model, checks the consistency and completeness of the project representation, provides access to and editing of the database and drives the interactive simulation. It controls the access to the user interface, the data management, the calculation engine and the result module. For people with no simulation knowledge, the PM offers a database of existing projects and extracts information from a particular model. A detailed description of the Project Manager's functionality can be found in [Han1998].

4.4 ESP-R GEOMETRY DATA MODEL

In ESP-r, the 3D geometry model representation is based on a common model hierarchy, in which the building is represented as a grouping of *zones* as shown in Figure 4.2.

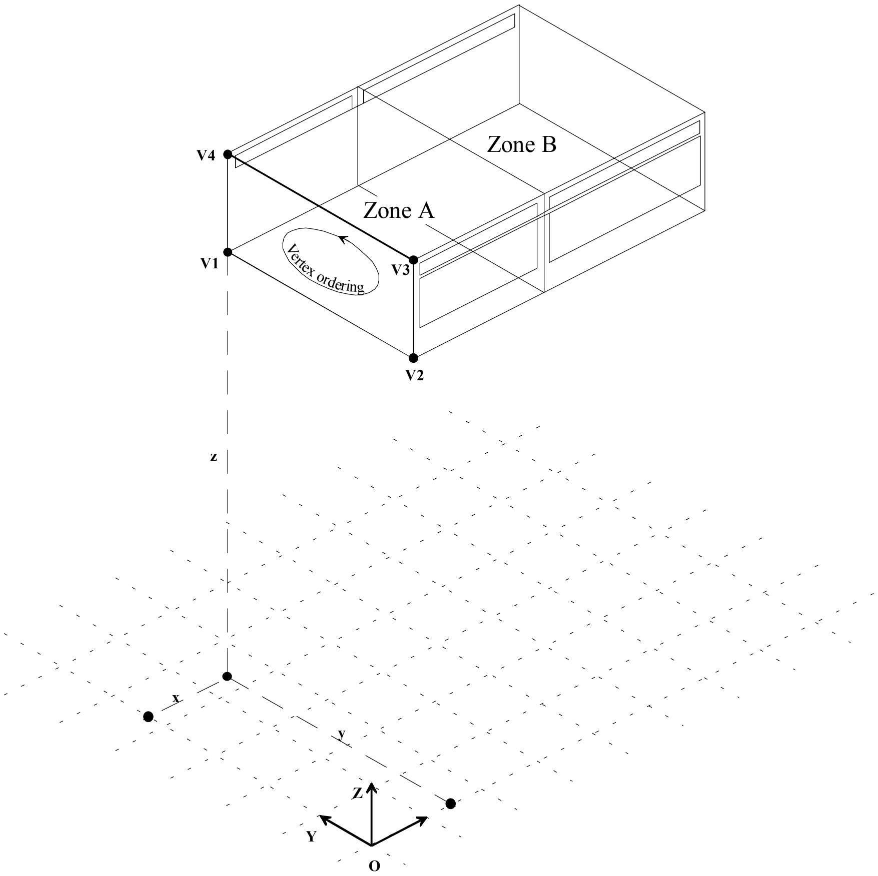


Figure 4.2 Example of the geometry representation of two zones in ESP-r. (V: vertices) (Model-fait main.dsf)

A zone is a volume bounded by connected surfaces, where each geometry surface is defined as a list of vertices oriented anticlockwise when looking from the outside. In the example presented in Figure 4.2, one of the surfaces (*A-East*) in zone *A* is delimited by the vertices *v1* to *v4*. Each vertex is defined by a set of three co-ordinates *x, y* and *z*. These natural language sentences used to describe the structure of the geometrical information can be described rigorously with the use of a conceptual language, whose primary goal is to provide a ready-to-use and expressive representation based on a specific vocabulary and grammatical structure. The use of such a conceptual language is not limited to the geometrical information and can be used for any data model representation. In the reminder of this document the data model will be presented with the NIAM (Nijssen Information Analysis Method) graphical modelling language [Nij1989], whose definition of the symbolism is summarised in Appendix G for casual reader.

Figure 4.3 is the conceptual transcription of the geometry representation presented in Figure 4.2, using the NIAM.

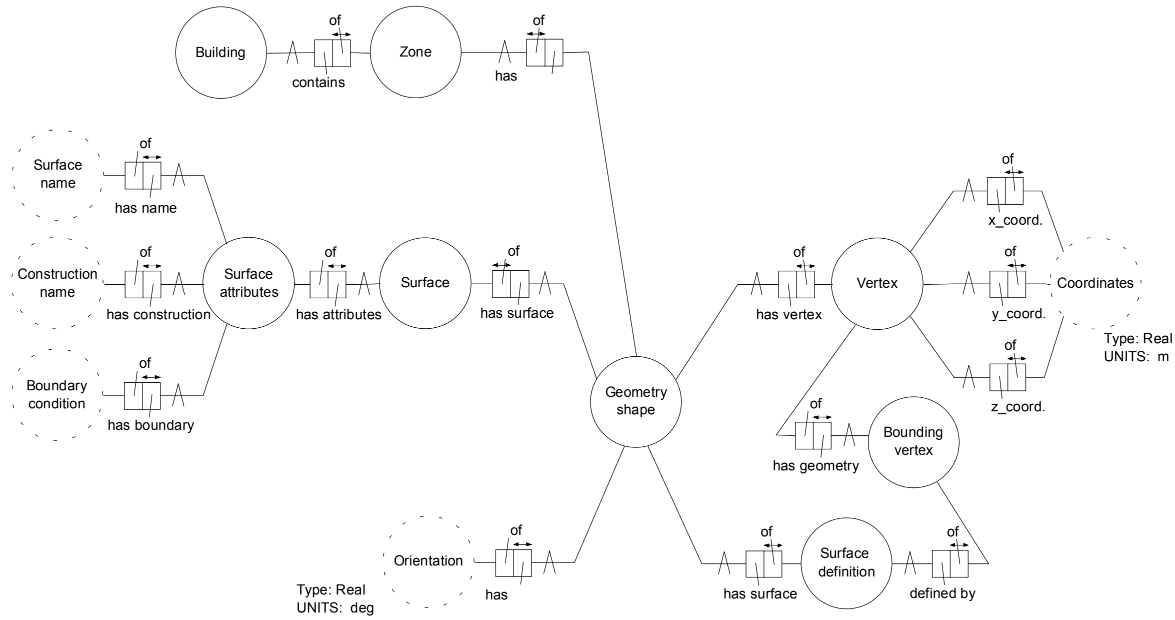


Figure 4.3 NIAM description of the geometry model in ESP-r (see example in Figure 4.2**)** (geometry ESP-r-epure.flo)

The Figure 4.3 expresses that the *Building* contains at least one *Zone*, and each zone has a *Geometrical shape*. The geometry of any surface is defined by its bounding vertices (such as *v1* to *v4* in Figure 4.2). Each vertex is defined by its *Coordinates* x, y and z. In addition, each enclosing surface of the zone has three *Surface attributes*: a *Surface name*, a *Boundary condition* (exterior, contiguous zone, adiabatic, etc.) and a *Construction name* attribute. The latter is referenced by Figure 4.5 and used to link the geometry model and the corresponding construction representation. Further information on ESP-r data model can be found in [Cla1995b; Han1998].

4.5 PHYSICAL ATTRIBUTES

There is currently no unified method that allows a multiple-view assessment based on basic material physical properties. For example, the photo-colourimetry attributes required for a lighting simulation do not provide any information on the environmental impacts of the material. Therefore, for each considered view, the corresponding physical attributes must be included within the data model. To achieve this goal, the iterative method presented in the previous chapter (Figure 3.7) has been applied to extend the physical information required by ESP-r to support the assessment of thermal, lighting, room acoustics and environmental performance.

The selection of physical attributes that represent the material and construction properties is limited to elementary attributes, which cannot be derived from other more elementary properties. For instance, thermal diffusivity and effusivity is not an elementary property because it can be derived from the density and the conductivity, which are elementary attributes as shown in Table 4.1.

Physical property	Description	Equation	Elementary attributes
Diffusivity	Material capacity to transmit a temperature variation	$\frac{\lambda}{\rho \cdot C_p}$	λ Conductivity ρ Density C_p Specific heat
Effusivity	Material capacity to absorb or resituate a thermal intensity	$\sqrt{\lambda \cdot \rho \cdot C_p}$	

Table 4.1 Definition of the material diffusivity and effusivity with the related elementary physical attributes.

The choice of storing elementary attributes reduces the data to key, the data volume and above all prevents inconsistency. Assuming a set of physical attributes that holds the diffusivity, the effusivity and the density. If for any reason the density has to be modified, the corresponding diffusivity and effusivity must be updated as well, otherwise the set of attributes will be incoherent. Using elementary attributes prevents this potential inconsistency.

The physical information required by a calculation method, but which is not related to the building element, is not taken into account. For example, some advanced day-lighting methods require the sky luminance distribution. As this property is not directly related to the construction materials, it is not included here.

As the data model becomes more exhaustive for a particular view, it will tend to become assessment method independent for that view [Cit1999a]. In other words, the more is known about an entity, the greater the relevant information that can be found or derived for any particular assessment method. Were the data model to include all possible information, there would be no need for a specific view to complete its local data model by adding supplementary information. Therefore, the physical model should include a set of material properties that is as exhaustive as possible. It should not be considered excessive to include in the physical data model properties that are not absolutely necessary, but should be seen as a simplification for future integrated simulation developments. The following sections detail the physical data model structure and the connection between the views and the construction description.

4.6 SOURCE AND UNIT ATTRIBUTES

An attribute is a specific information or property of an entity or a relationship type. For instance, a *material* entity type may be described by attributes such as its *density* or *conductivity*. Each attribute has a type, which defines the type of information, such as an integer, a real, a string, etc. The attribute domain is the predefined range of possible values that may be assigned to an attribute. It can be as extensive as the domain of real numbers or as limited as one alphabetical character. For instance, the attribute domain of the *solar absorption* attribute of a *material* is [0;1]. In the remainder of this chapter, the attribute type and domain are defined only when it is not evident.

To avoid any confusion, an attribute that represents a physical property is characterised by its source of origin. Defining the source attributes is an important issue. Although most of the physical properties of a material are well known and even defined in standards such as the SIA 381/1 [SIA1980], there are properties that are not standardised. This is the case for instance for the emerging domain of the environmental impact assessment. To assess the life cycle impact of a building, the data used may originate from various references and it is important to keep a track of the data origin. More generally, any attribute has little value if its source is unknown. To keep the transparency of the data origin, it is important to give the reference from where a data was extracted.

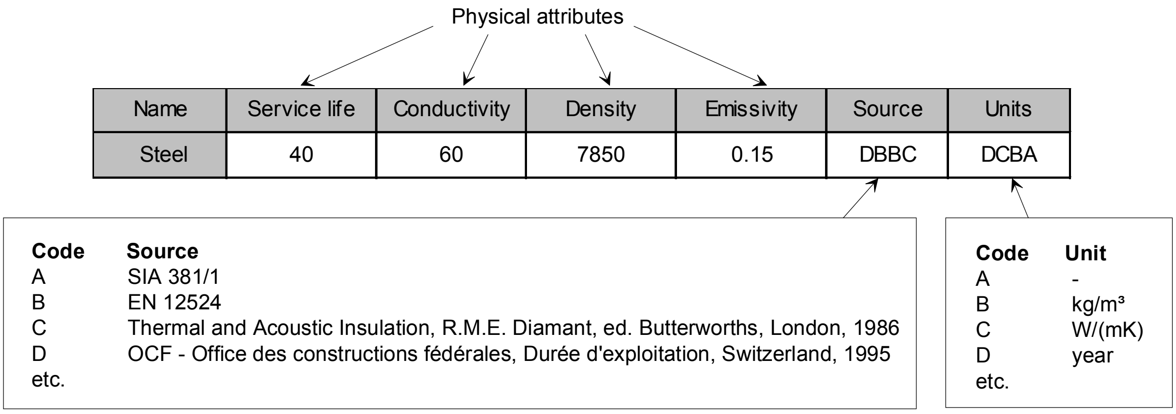


Figure 4.4 Management of source and unit attributes. (Units and sources.dsf)

The solution developed in this work is to store one string of letters that characterises the sources. The letters' order in the string corresponds to the attributes' order of occurrence in the record. Figure 4.4 shows the example of the material *Steel*, for which the reference of the *Service life* attribute is code D (OCF) in the source list, code B (EN 12524) for the *Conductivity* and *Density*, and C (Diamand & Butterworths) for the *Emissivity*. The same approach is used to define the attribute unit. This representation of units and sources has the advantage of compacting the information.

4.7 DATA UNCERTAINTY

It is generally assumed that a database is a collection of 'perfect' data, in the sense that they are error-free. This might not be true for certain views, for which the data may be tainted with incertitude, related to the reliability of the data. To appraise the difference between the results of two alternative projects MacDonald [Mac1999] has implemented in ESP-r the use of data uncertainty for sensitivity analysis. A differential sensitivity analysis and a Monte Carlo analysis enable the assessment of the effects of input variations on the result. This approach has been used in the new database design, but is beyond the scope of the presented work.

4.8 CONSTRUCTION

The *Construction* entity holds the information at the construction level and records attribute names for different views and the layer composition as shown in Figure 4.5. Each construction is univocally defined by its *Construction name*, which is used as the connecting attribute with the geometry representation of an element (referenced in Figure 4.3).

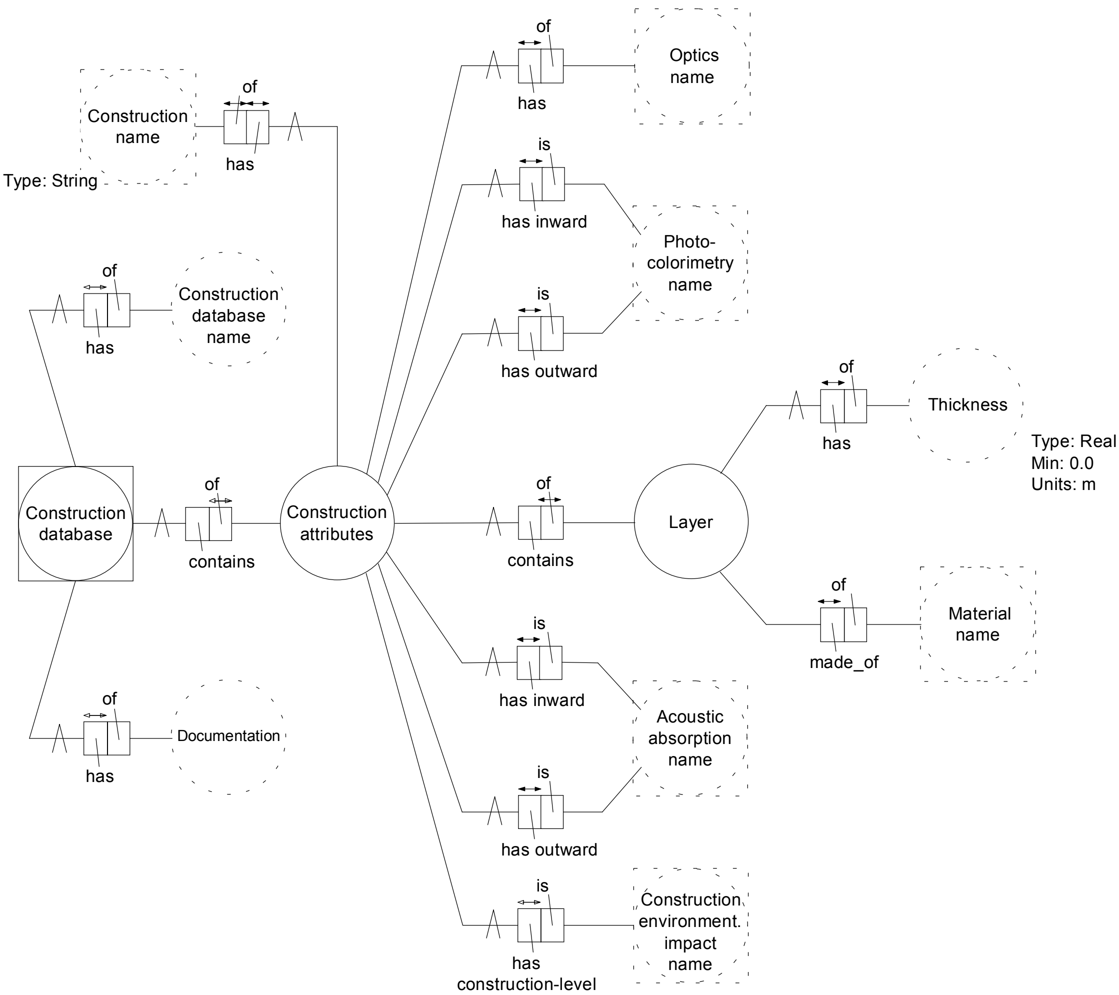


Figure 4.5 Attributes at construction level (constructionESP-r.flo)

Each construction side (inward and outward) has a *Photo-colourimetry name* and an *Acoustic absorption name*, which are used respectively for lighting (referenced in Figure 4.10) and room acoustics views (referenced in Figure 4.9). The construction may include a *Construction environmental impact name*, which holds environmental information at the construction-level (referenced in Figure 4.13). Transparent construction may have optical information referenced by its *Optics name* in Figure 4.8.

Finally, a construction consists of one or more *Layer(s)* defined by a *Material name* referenced in Figure 4.6 and its corresponding *Thickness*. This representation of a building element as a multi-layered construction is suitable for building components made of a superposition of uniform layers. Heterogeneous element can be decomposed into smaller homogeneous constructions.

4.9 MATERIAL

The material information includes the attributes intrinsically related at the material-level as shown in Figure 4.6. It includes the *Hygro-thermal name* (referenced by Figure 4.7), the *Photo-colourimetry name* (referenced by Figure 4.10) and the *Room acoustics name* (referenced by Figure 4.9) attributes. Each material is univocally defined by its *Material name*, which is referenced in Figure 4.5 for the construction representation.

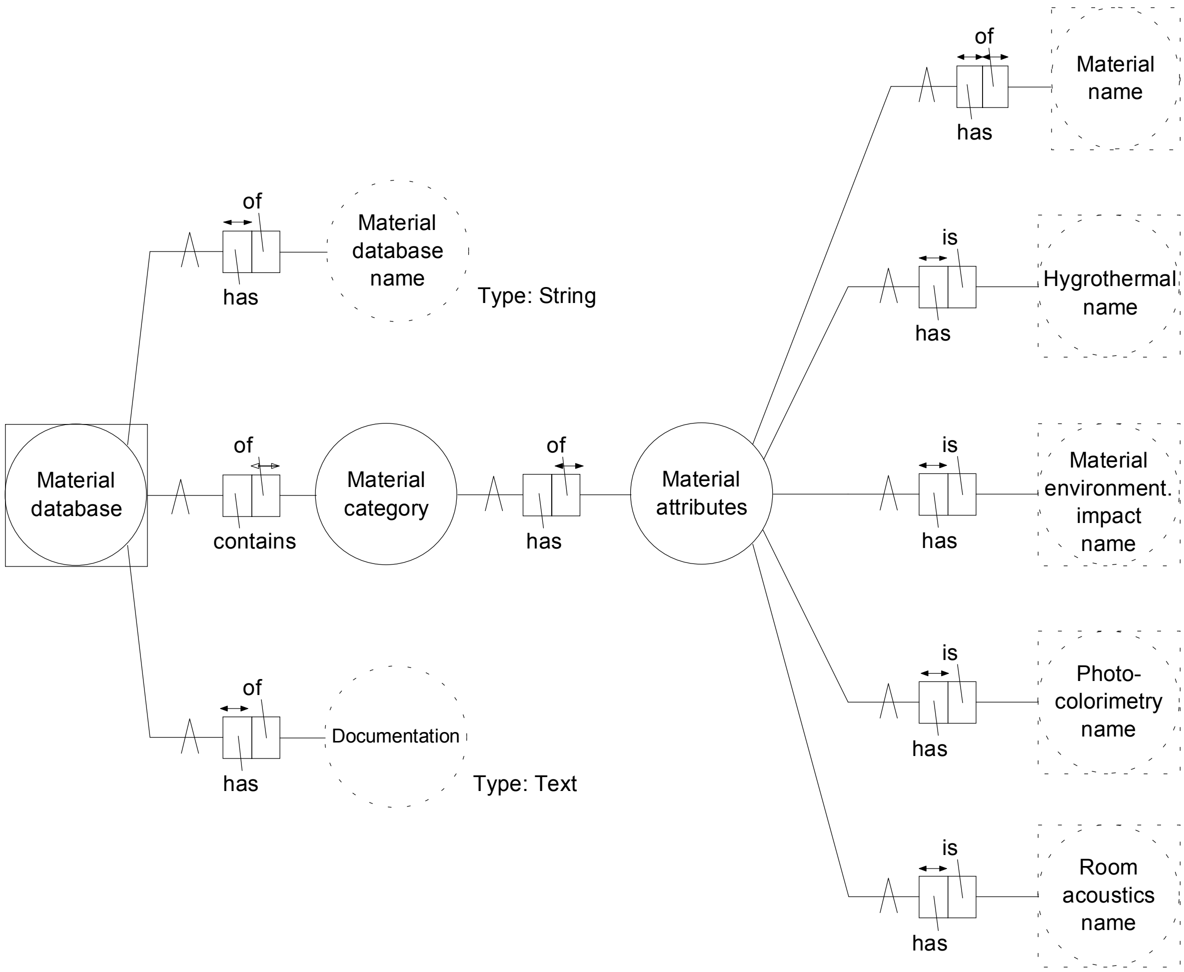


Figure 4.6 Material attributes diagram. (materialESP-r2.flo)

The colourimetry and photometry attributes are referenced by the *Photo-colourimetry name* at the material level (Figure 4.6) and at the construction level (Figure 4.5). At the material level, they characterise the 'natural' attributes of the material, such as greys for concrete or browns for woods. At the construction level these attributes are necessary to define the external surfaces colour of a construction constituted from different materials. At the construction level the photo-colourimetry attributes of both its external surfaces should automatically be set equal to the attributes of the external materials.

The room acoustics information is referenced by the *Room acoustics name* at the material level (Figure 4.6) and at the construction level (Figure 4.5). At the material level, the acoustic absorption name characterises the absorption of a massive piece of material or of one on a rigid support.

4.10 HYGRO-THERMAL

The original hygro-thermal attributes in ESP-r encompassed the traditional *Density*, *Conductivity*, *Specific heat*, *Moisture diffusion resistance*, *Long wave emissivity*, *Short wave absorption* as shown in Figure 4.7.

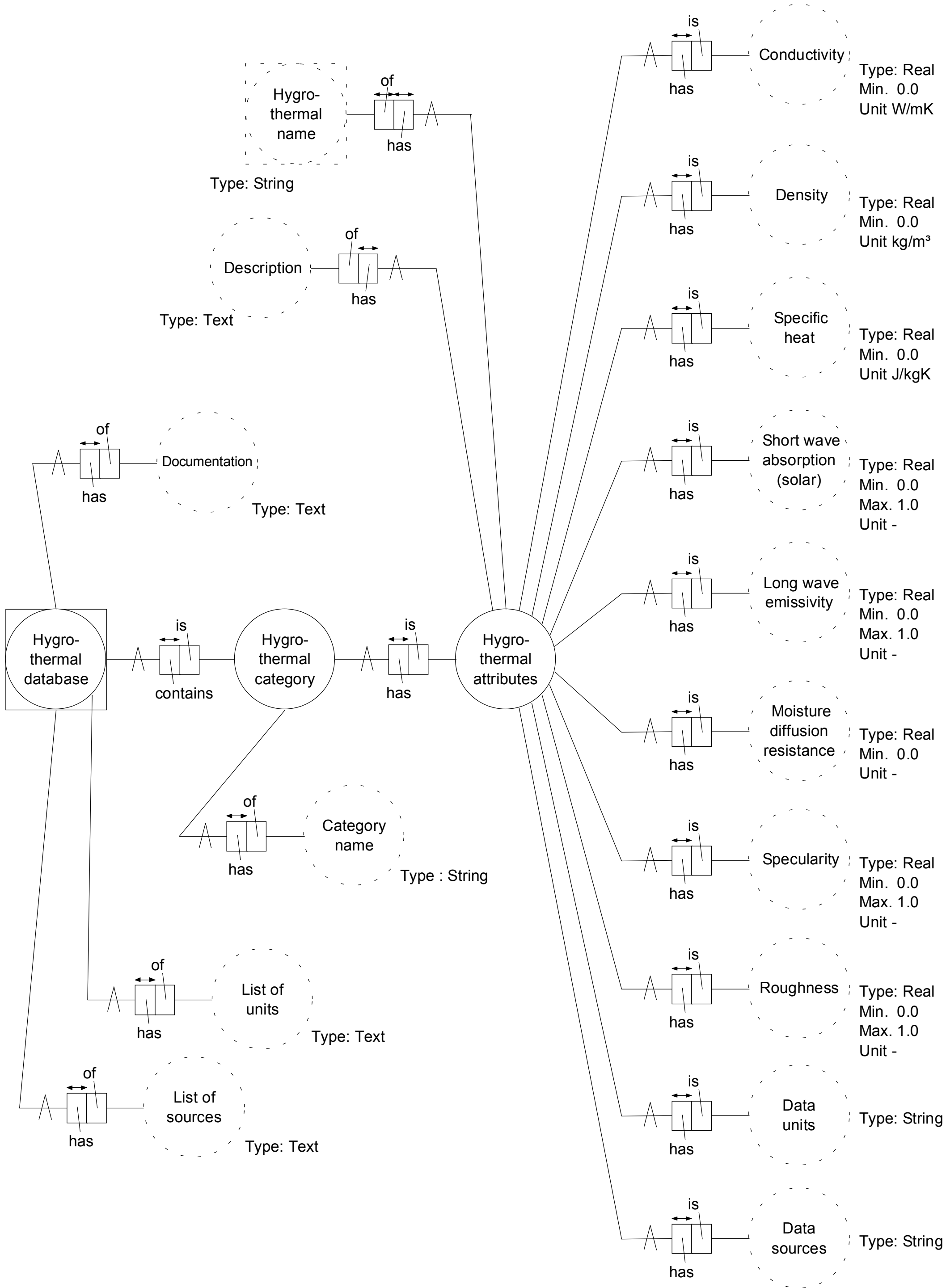


Figure 4.7 Hygro-thermal attributes diagram.

Supplementary attributes have been added to the hygro-thermal view to support advanced calculation methods used in simulation [Tav1996]: (1) the *Roughness*, which is the standard deviation of the surface height over the auto-correlation distance of this deviation, and (2) the *Specularity*, which is the rate of radiation reflected (or transmitted) by specular mechanism. But, the U-value has not been considered here because it is not an elementary property and can be calculated from the construction composition and the elementary hygro-thermal attributes listed in Figure 4.7.

4.11 OPTICS

The optical information for the transparent construction is based on the original aspect model used in ESP-r. It enables a detailed appraisal of the solar gains and transmitted light for energy and lighting assessments. It requires the total visible transmittance and solar transmittance of the construction, and the solar absorptivity of each layer for different incidence angles as shown in Figure 4.8.

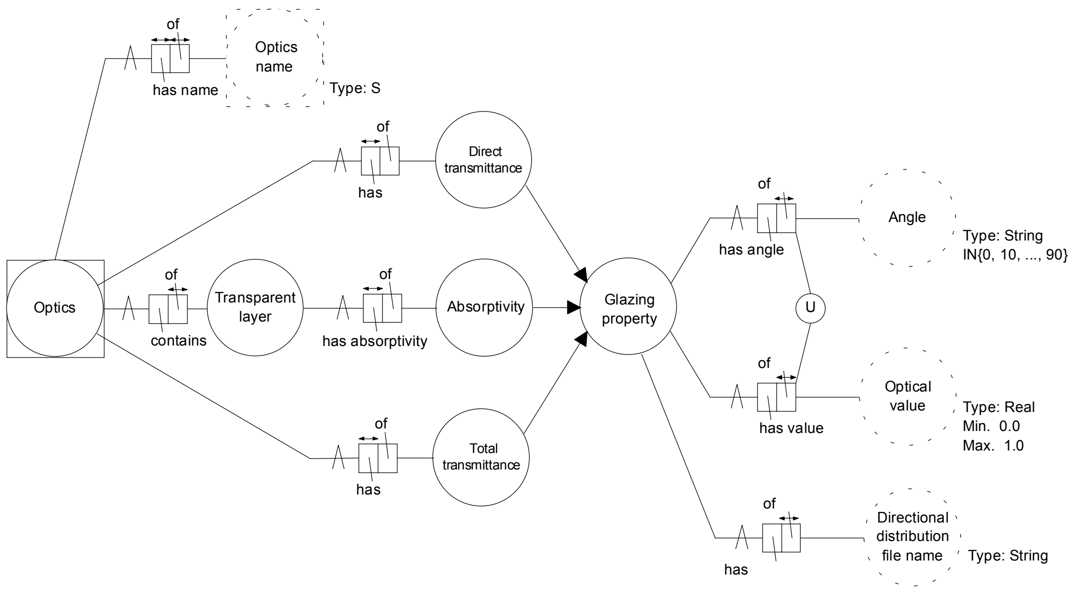


Figure 4.8 Optical attributes diagram. (OpticsESP-r.flo)

The optical properties of a glass pane are almost constant between 0° and 40° and nil at 90° (0° means normal incidence). To assess accurately the system performance, the optical attributes are given for each 10°. For other angles of incidence, the optical properties can be extrapolated. This representation of the optics is acceptable for systems with a normal-axis symmetry property, such as a glass pane. For complex daylighting systems, the attributes can be expressed through a directional reflectance/transmittance/absorption distribution, which describes the angular distribution of the properties depending on the incident light. The representation can either be a mathematical function or a table of data, which gives the reflectance for a set of incidence angles as done for instance by Andersen [And1999]. Due to the variable amount of data, which depends on the resolution of the incident angle sampling, the information could be handled via the name of an external file that extends the physical information stored in the optical entity.

4.12 ROOM ACOUSTICS

From a theoretical point of view, it might be possible to derive the *Acoustic absorption coefficients* of a material. This would require material properties, such as the tortuosity. Unfortunately, most of these properties are known for a limited number of materials and could be difficult to estimate [Was1996]. In practice, the absorption coefficients used in room acoustics are based on measurements made in a standardised reverberation room (see § 6.4).

The *Acoustic absorption coefficients* are expressed either in the one octave band (125, 250, 500, 1000, 2000 and 4000 [Hz]) or in the one-third octave band (100, 125, 160, 200, 250, 315, 400, 500, 630, 800, 1000, 1250, 1600, 2000, 2500, 3150 and 4000 [Hz]). To support both representations, the data model supports the storage of the one-third octave band coefficients as shown in Figure 4.9. If only octave band data are available, it is possible to extrapolate the missing values before their storage and it would be relevant to notice it in the record description.

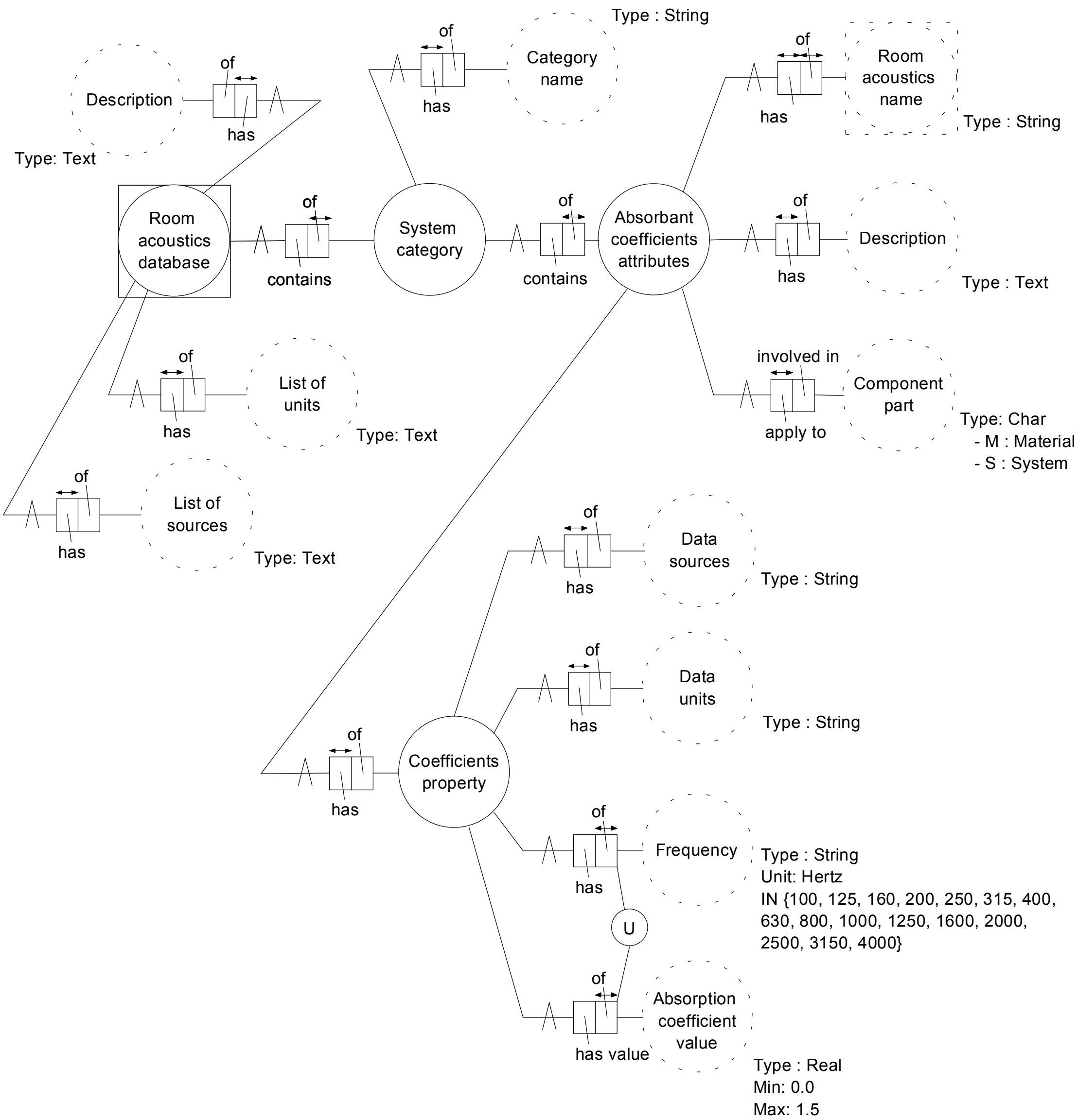


Figure 4.9 Room acoustics attributes diagram. (room acousics2.flo)

4.13 PHOTO-COLOURIMETRY

Some simplified analytical methods, such the BRE split-flux formula [CIBSE1987] require only the surface *Reflectance* to assess the lighting distribution in a space.

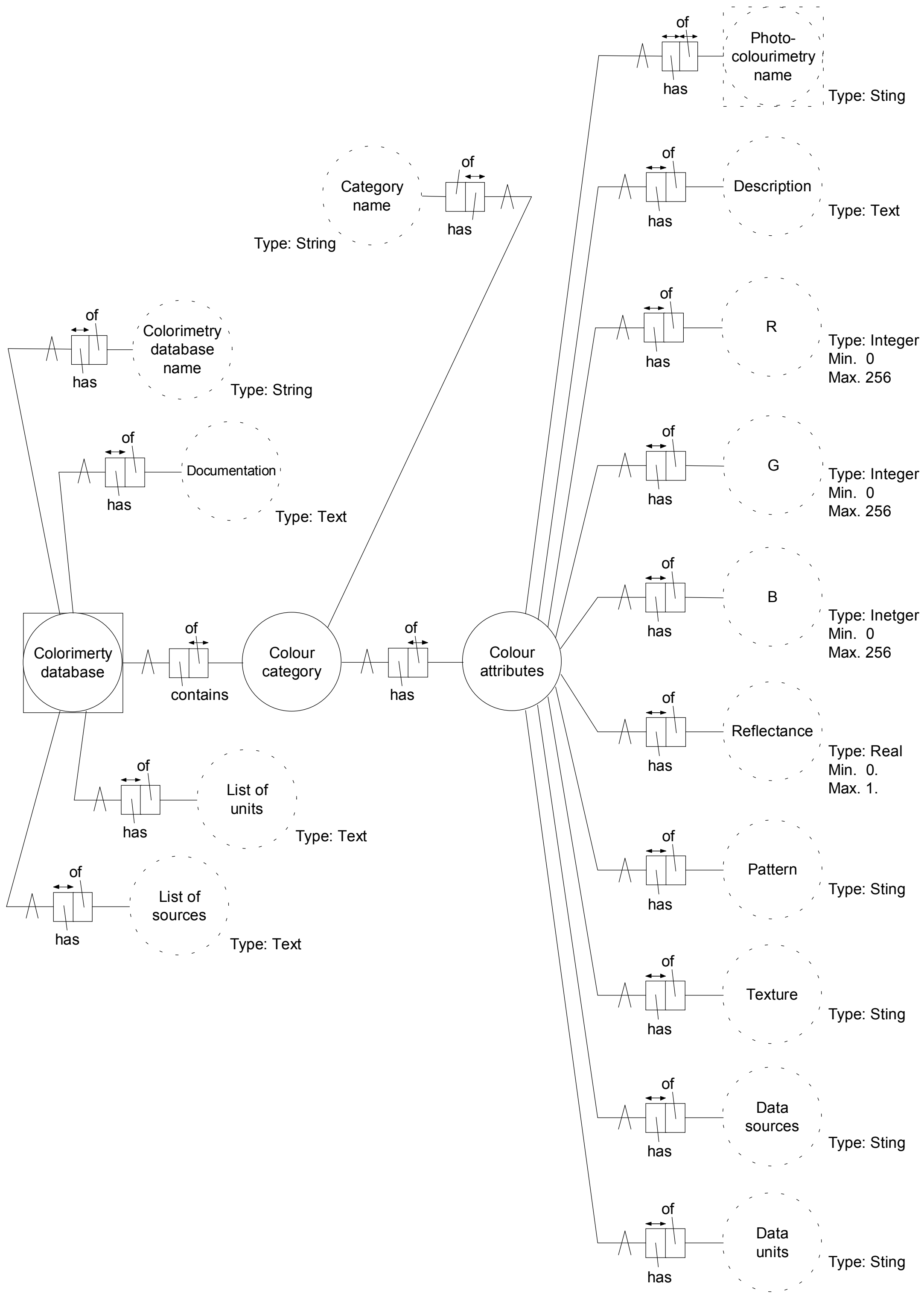


Figure 4.10 Photo-colourimetry attributes diagram. (Photo-colorimetryNIAM.flo)

More advanced simulation methods, such as ray tracing, require more refined photo-colourimetry properties that are the chromatic co-ordinates and the reflectance of the material [Gla1989]. Among the different available chromatic models, the *RGB* colour model has been selected because it is a hardware-oriented system used with visual display units (VDU).

As shown in Figure 4.10, the photo-colourimetry attributes also include *Texture* and *Pattern*, which are used to modify the surface appearance in creating visual effects in advanced simulation programmes [Lar1998]. It may also require the material roughness and specularity. These two attributes have already been stored in the hygro-thermal properties as they are also used for thermal simulation. To avoid redundancy, they are not stored in the photo-colourimetry entity. If the lighting simulation requires such information, these properties can be extracted from the hygro-thermal attributes.

4.14 ENVIRONMENTAL IMPACTS

This section is dedicated to the information required to perform an evaluation of the environmental impacts generated by the building during its whole life. Currently, there is no unanimous method to assess the environmental impact of a building. Nevertheless, the environmental attributes listed below support a detailed life cycle assessment, according to the framework proposed by the International Organisation for Standardisation (ISO) [ISO1997].
The term ‘impact’ is used as a generic word to express any modification of the initial environment. These environmental attributes can result either from a valuation method (unique index), from characterisation (profile made of several effects), from a list of impacts extracted from the inventory table or a mix between these different approaches. Therefore, the entity *Process cost* is used to represent the generic attributes of the environmental impacts as shown in Figure 4.11.

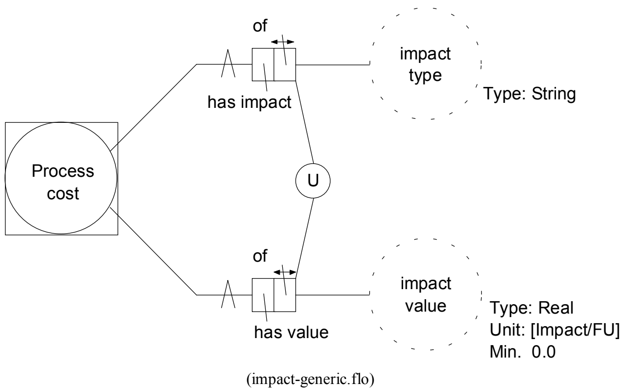


Figure 4.11 Generic representation of the environmental cost.

This generic representation expresses the possibility for a process to entail a set of environmental impacts. It is not necessary here to define in detail what these impacts are (these aspects are treated more in detail in the next chapter dedicated to the environmental impacts assessment). It should be only kept in mind that the process cost can be quantitatively characterised with one or several impact values with appropriate units, expressed in unit of the impact type (Impact) per functional unit (FU). More generally, the same model may be used to assess any life cycle cost, such as for instance the financial cost, as long as it fits the proposed structure.

4.15 TRANSPORT

The environmental impacts generated by transport may occur in several phases of the building life. To enable a flexible use of transport information, the corresponding environmental impacts are referred by the *Transport name*. This enables the environmental aspect model to refer at various life cycle phases to the appropriate transport information without including redundancy. The means of transport are subdivided into categories to help the classifying of the records in a meaningful order. There is no hierarchical implication in this classification, i.e. there is no inheritance aspect related to the classification. A possible way of organising the means of transport is to group them by type, such as road, air, railway, etc. Each environmental attribute is related to the specific impacts generated by the transport as shown in Figure 4.12.

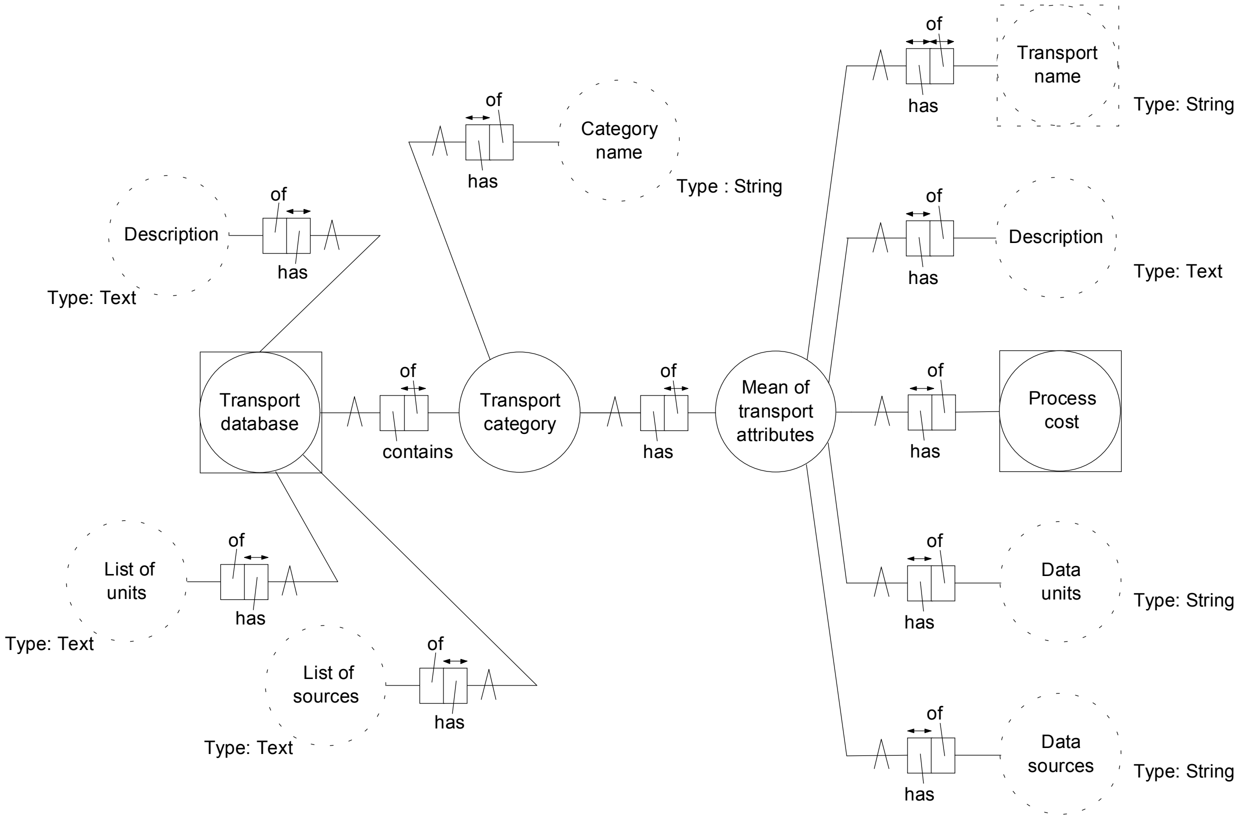


Figure 4.12 Transport attributes diagram. (Transport_Niam.flo)

The information related to a means of transport includes the *Transport name* and the specific *Process cost* generated during the transport process. The transportation distance is not stored at this level because a means of transport can be used to cover different distances. To keep the flexibility and avoid information redundancy, it has been preferred to store the covered distance at the level where the *Transport name* is referenced (see Figure 4.13, Figure 4.14 and Figure 4.18).

4.16 ENVIRONMENTAL INFORMATION AT CONSTRUCTION-LEVEL

At construction-level, the environmental information holds attributes that are project dependent, i.e. may not be known before the construction is defined. Most of these attributes are related to the transport and assembly of a prefabricated element. During the transportation phase of a prefabricated element, i.e. between the construction site and the building site, several means of transport may be used. Each possible means of transport requires a *Transport name*, a *Transport distance* and has a *Breakage rate* for that transported element as shown in Figure 4.13. At the building site, the assembly of the prefabricated element on the building is referenced by the attribute *Assembly on building name* in Figure 4.16.

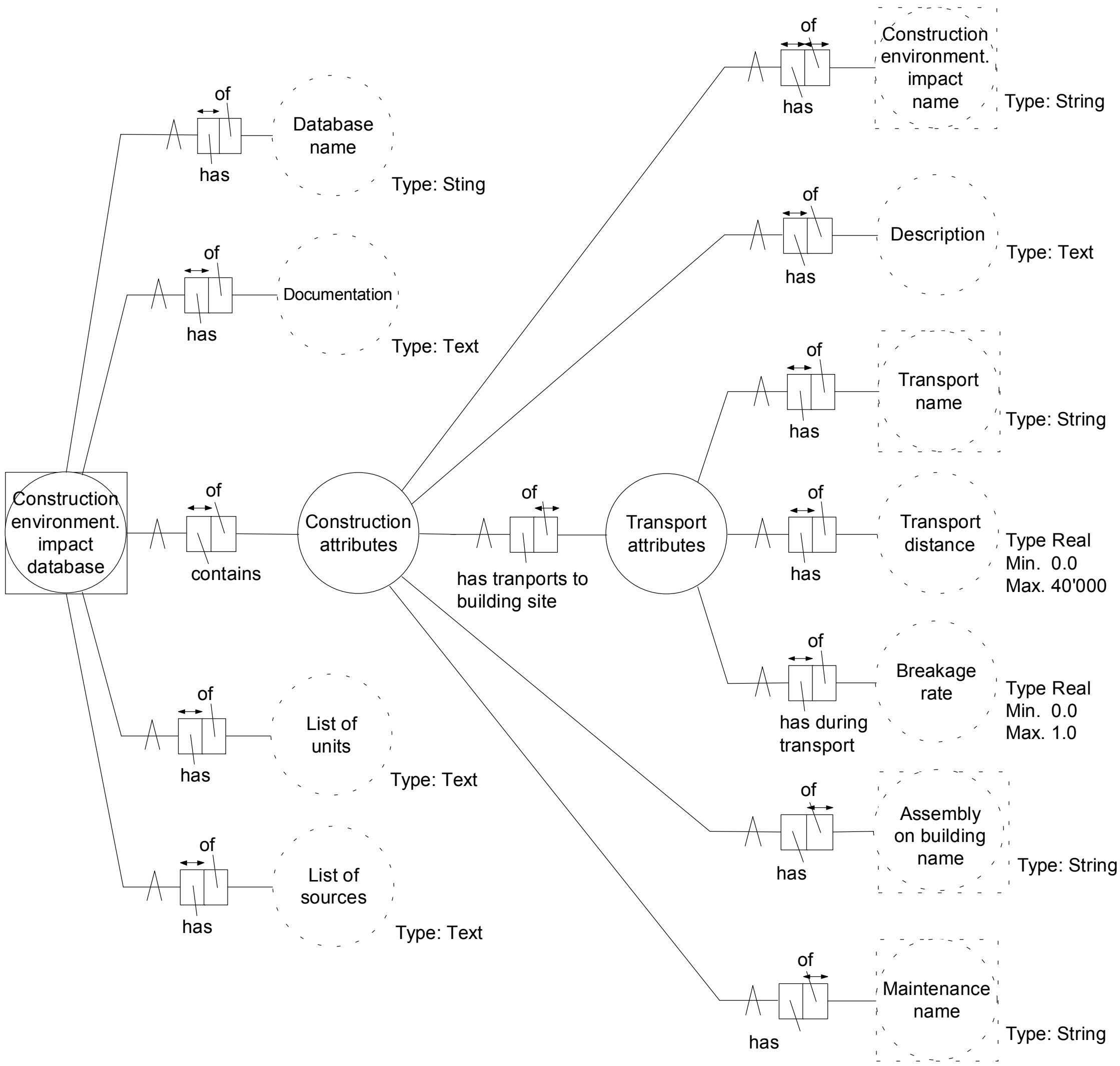


Figure 4.13 Environmental attributes at construction-level. (Constructions impacts - LCA_NIAM2.flo)

For any building element, prefabricated or not, the maintenance process of the construction is referenced by the *Maintenance name*, which attributes are define in Figure 4.17. All these attributes are univocally define by the *Construction environmental impact name*, which is used to reference the environmental views at the construction-level in Figure 4.5.

4.17 ENVIRONMENTAL INFORMATION AT MATERIAL LEVEL

The environmental information at the material-level holds intrinsic attributes that may be considered to be independent from material use. As shown in Figure 4.14, it includes the *Process cost* of the material manufacturing, the *Service life* of the material (used to estimate the replacement frequency of the material during the building life) and the *Assembly loss rate* of material generated during the construction assembly. The environmental information at material level is referenced by the attribute *Material environmental impact name* to the material views in Figure 4.6.

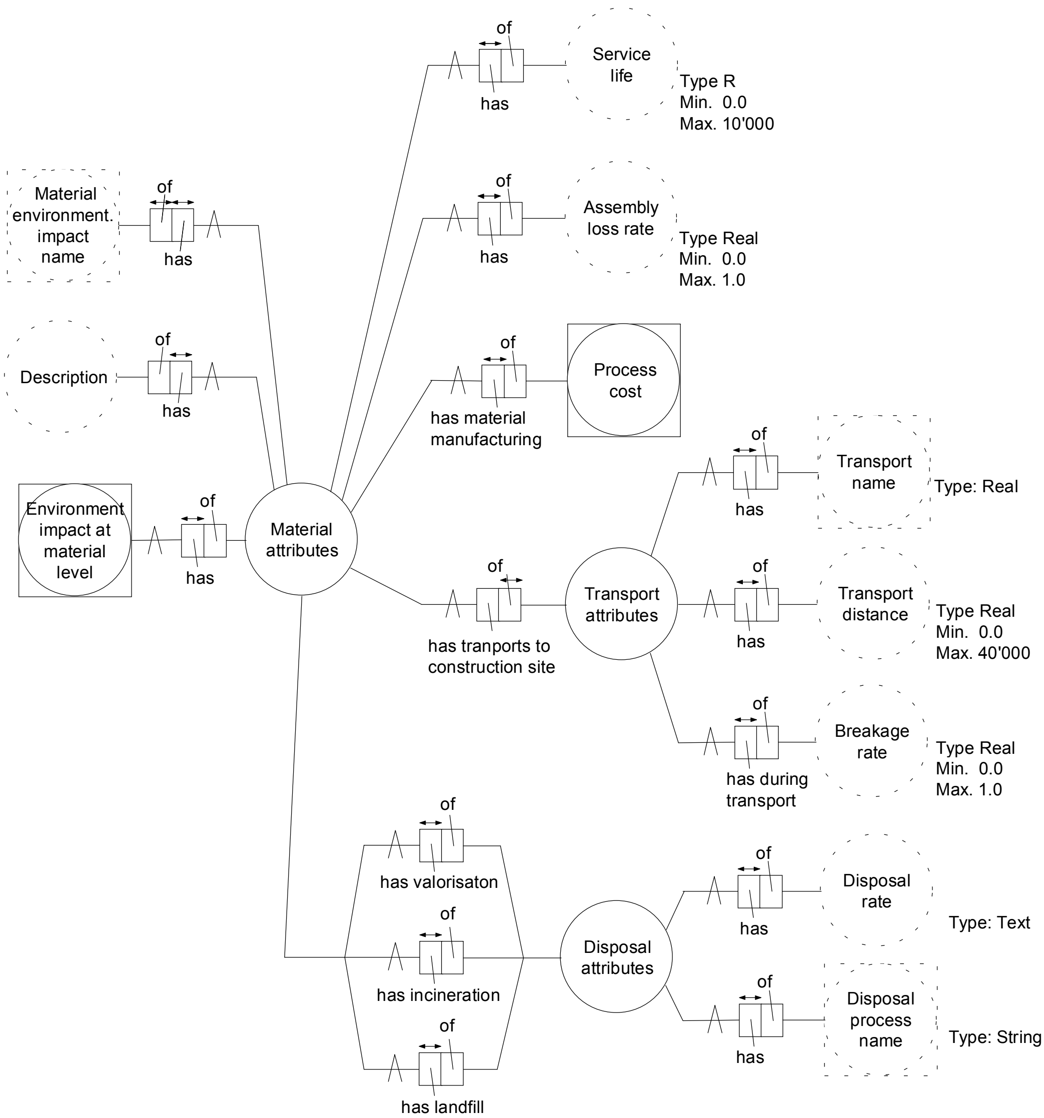


Figure 4.14 Environmental attributes at material-level. (Material - LCA.flo)

The information required to assess the impact generated during the material transport from the manufacturing site to the construction site includes the *Transport name* (referenced by Figure 4.12), plus the *Transport distance* and the possible *Breakage rate* for that means of transport. Finally, the assessment of the waste disposal requires for the three possible elimination channels the *Disposal rate* and the *Disposal process name* (referenced by Figure 4.18) for the considered material.

4.17.1 Construction assembly

The construction assembly aspect model contains the information related to the environmental impacts generated during the assembly of a construction and includes the construction assembly *Process cost* as shown in Figure 4.15. The *Construction assembly process name* is referenced at the construction-level by Figure 4.13.

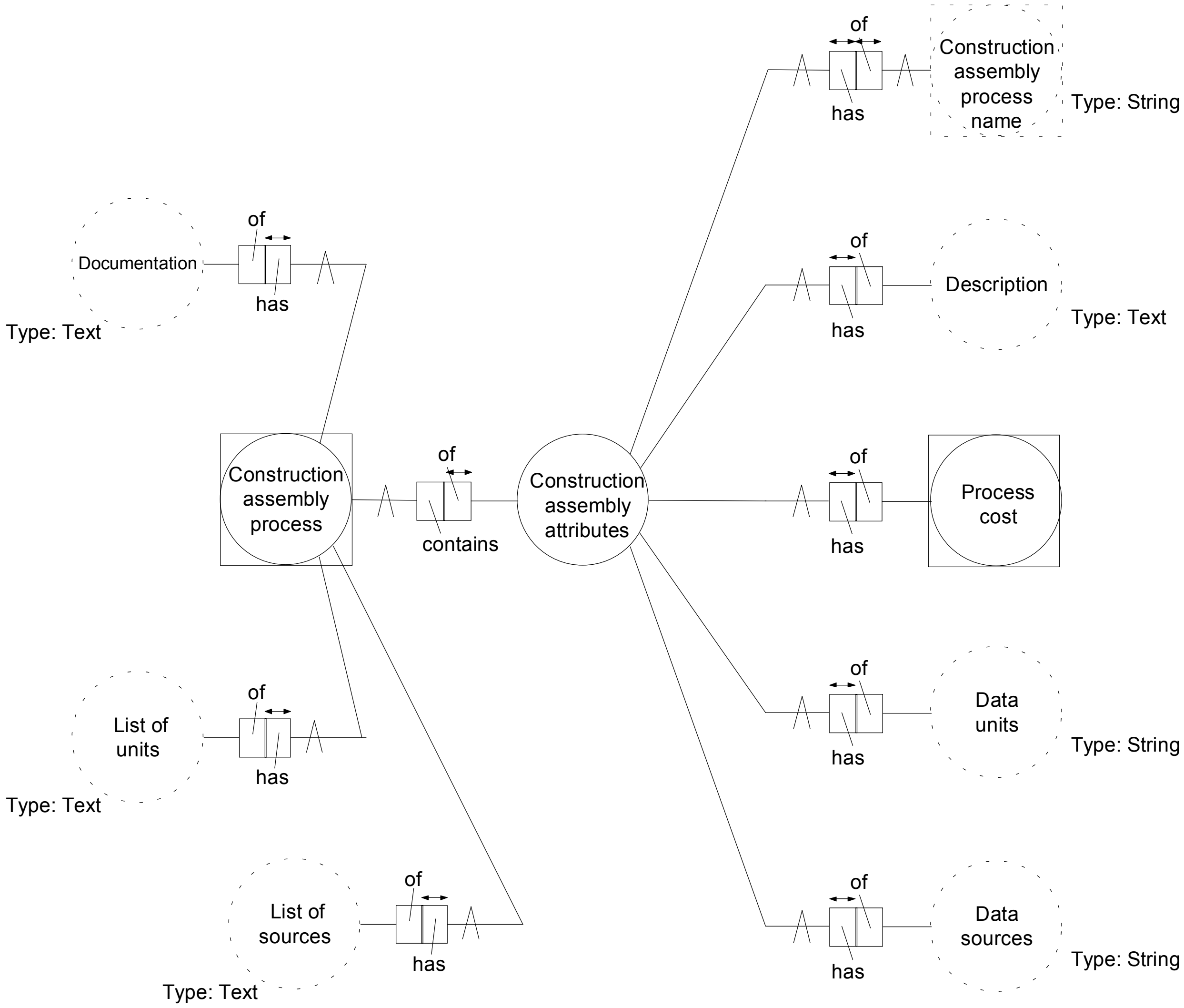


Figure 4.15 Construction assembly attributes. (construction assembly LCA_NIAM.flo)

4.17.2 Placement of a prefabricated construction on building

This environmental information is related to the impacts generated during the placement of the prefabricated construction on the building. This aspect model requires only the specific *Process cost* as shown in Figure 4.16 and is referenced by the *Assembly on building name* at the construction level (Figure 4.13).

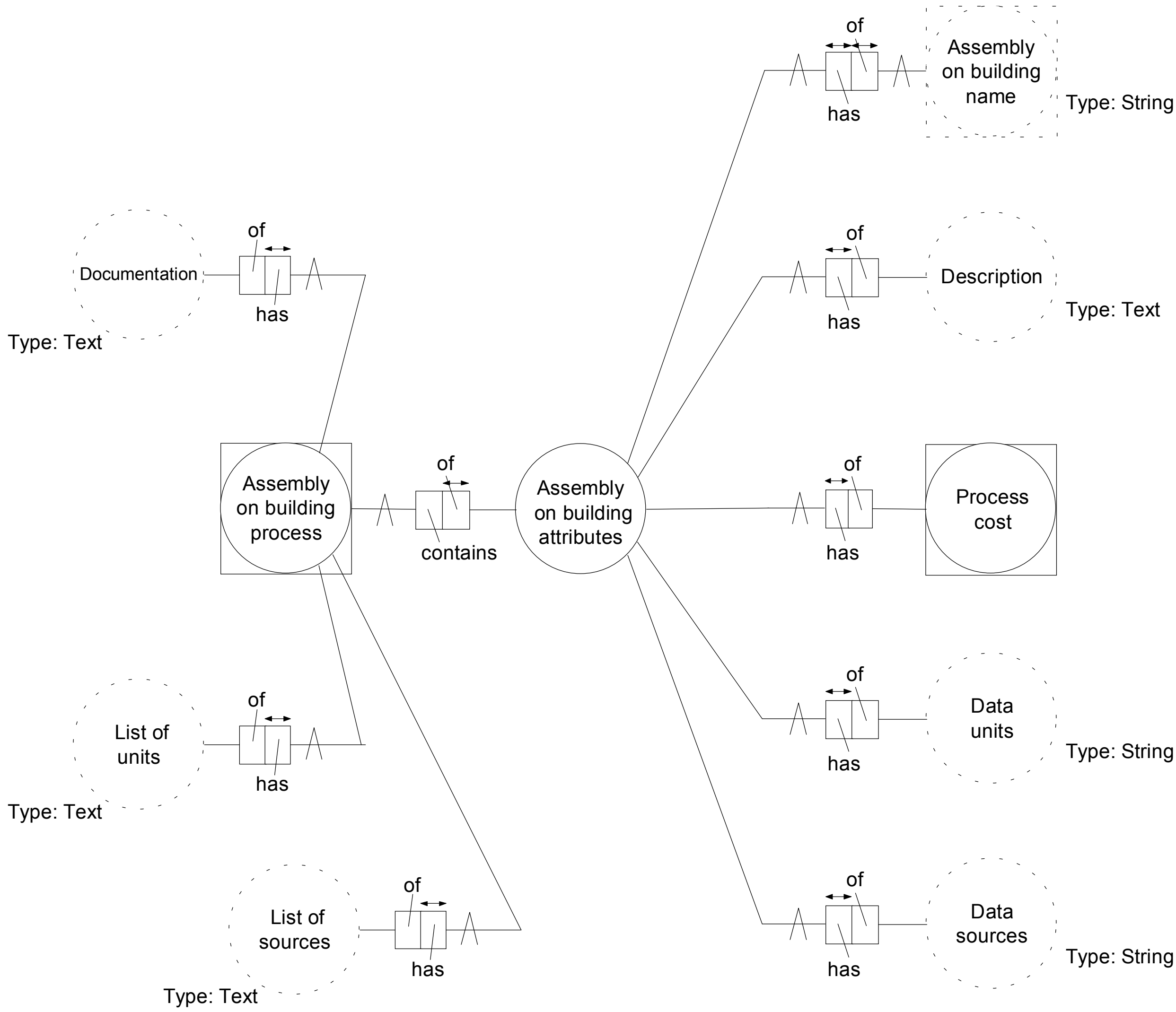


Figure 4.16 Attributes of the assembly of prefabricated element on project. (assembly_on_project_LCA_NIAM.flo)

4.17.3 Maintenance

The calculation of the environmental impacts generated by the maintenance of a construction during the building life requires the *Annual maintenance frequency* of the process and the specific *Process cost* generated during the maintenance as shown in Figure 4.17. It is also possible to indicate to which *Construction part* (perimeter or surface) the maintenance process is applied.

The impacts generated by the material replacement do not require supplementary information, except the material *Service life*, which is extracted from the environmental information at material level (Figure 4.14).

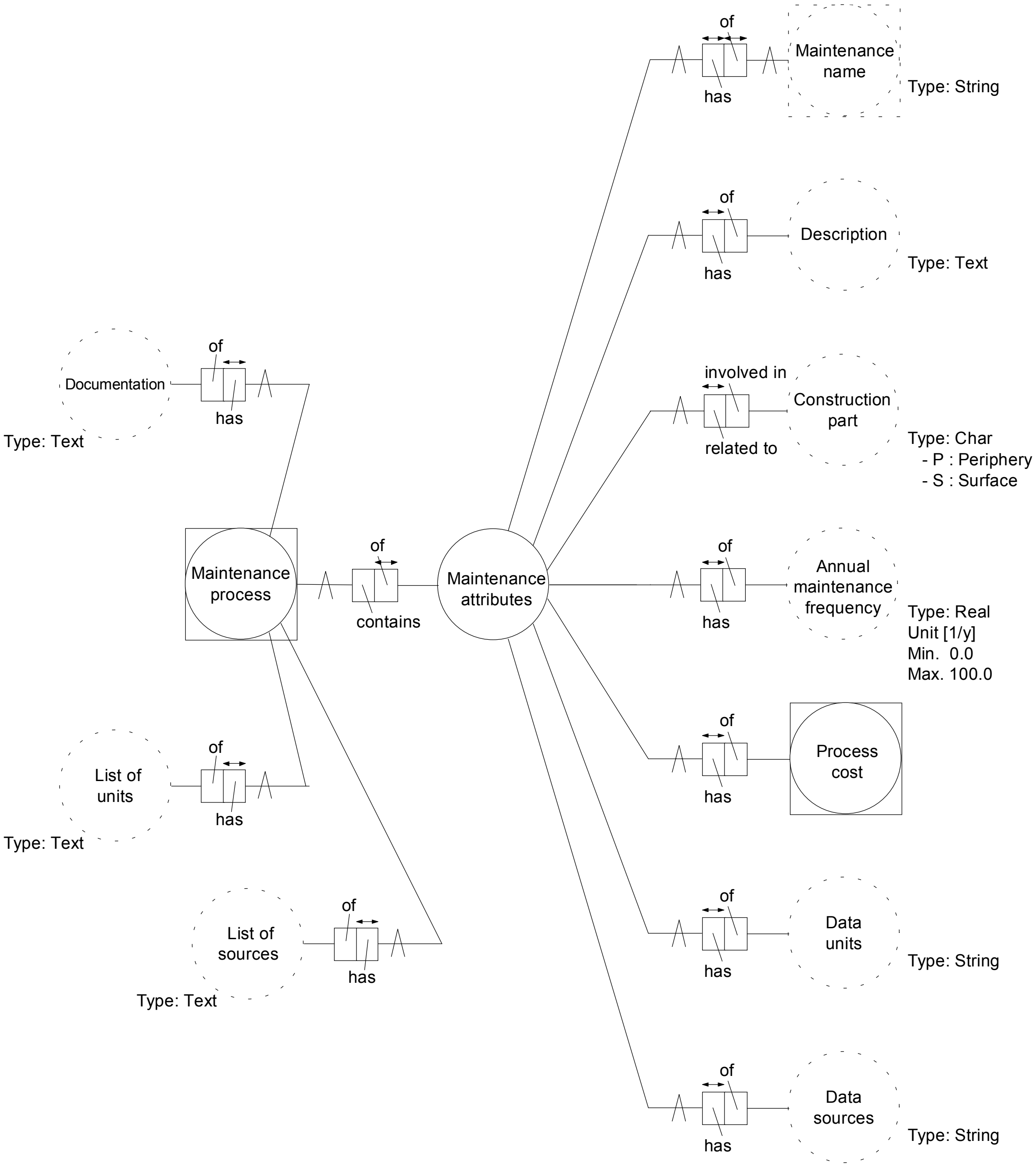


Figure 4.17 Maintenance attributes diagram. (MaintenanceLCA_NIAM.flo)

4.17.4 Disposal management

The attributes required to assess the material waste disposal include the specific *Process cost* generated by the disposal process and the attributes related to the disposal transport from building site to the waste management site, as shown in Figure 4.18.

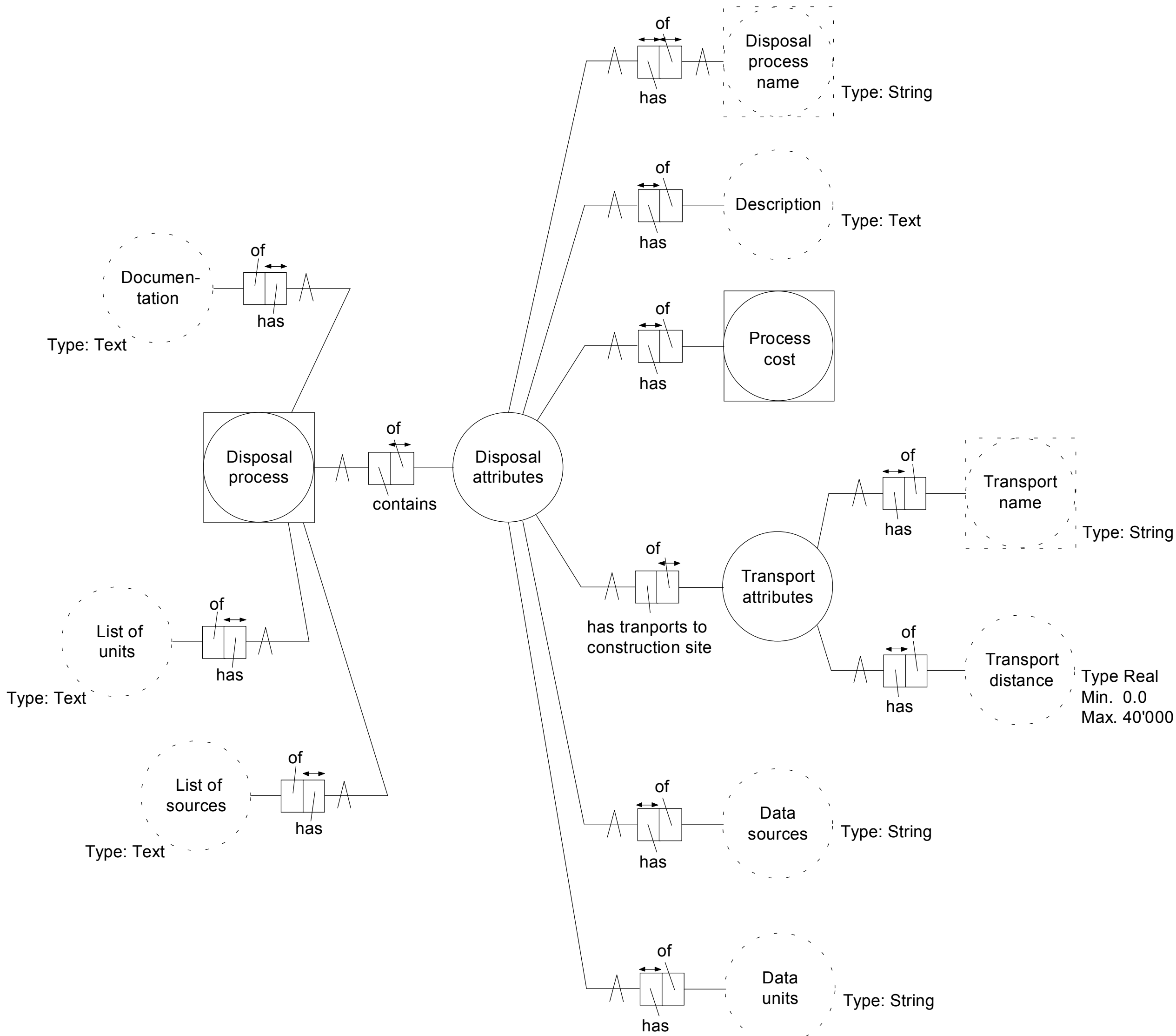


Figure 4.18 Disposal attributes diagram. (disposal_processLCA_Niam.flo)

The disposal process is referenced by the *Disposal process name* in the environmental information at the material level (Figure 4.14) that also includes the disposal rate for the three possible channels management and the corresponding transportation process to the disposal site.

The waste can be transported with several means of transport. For each journey, the *transport attributes* hold the name of the corresponding means of transport and the covered distance. Compared to other phases where transport was involved, no breakage and loss rate has been considered, because they are not relevant in the case of waste material.

4.18 ASSESSMENT METHODS

Table 4.2 summarises the assessments methods supported by the previous physical attributes (defined in Figure 4.5 to Figure 4.18) within the framework of an integrated assessment of building performance.

Assessment methods
Thermal • Thermal transmittance [CEN1996a] • Dynamic characteristics, [CEN1999] • Steady-state energy consumption [CEN1998] • Dynamic behaviour: Nodal network, response factor [Cla1985]
Ventilation • BSI [BSI1980] • ASHRAE [ASH1985] • Hybrid [Maa1993] • Flow/system network [Hen1991] • Zonal [All1995] • CFD [And1995]
Lighting • Lumen [IESNA1989] • Split-flux method [CIBSE1987] • Radiosity [Mod1982] • Ray-tracing [Gla1989]
Room acoustics • Sabine, Eyring, Milington, Pujolle, etc. [Jou1997] • Image Source Model [Lee1988] • Radiosity [Lew1993] • Ray-tracing [Kul1984] • Cone/pyramid Tracing [Fai1995] • Hybrid [Lew1993], [Vor1989]
LCIA • Life cycle assessment according to ISO [ISO1997]. Can be used with any indicators such as the Ecopoints 1998 [BUW1998], Eco-indicator 99 [Goe1999] and EPS [Ste1999]

Table 4.2 Summary of the calculation methods supported by the physical data model.

Occupant comfort assessment methods are not listed in Table 4.2 as their appraisal ensues from the building performance obtained with the calculation methods.

4.19 IMPLEMENTATION IN ESP-R

In the framework of the developments undertaken in this work, it has been decided to implement the physical data model in parallel in ESP-r developments, which permits checking the feasibility of the proposed approach without affecting the normal development of the Project Manager. To avoid any conflict with the existing project description, a new database manager has been developed for the ESP-r suite, as shown in Figure 4.19.

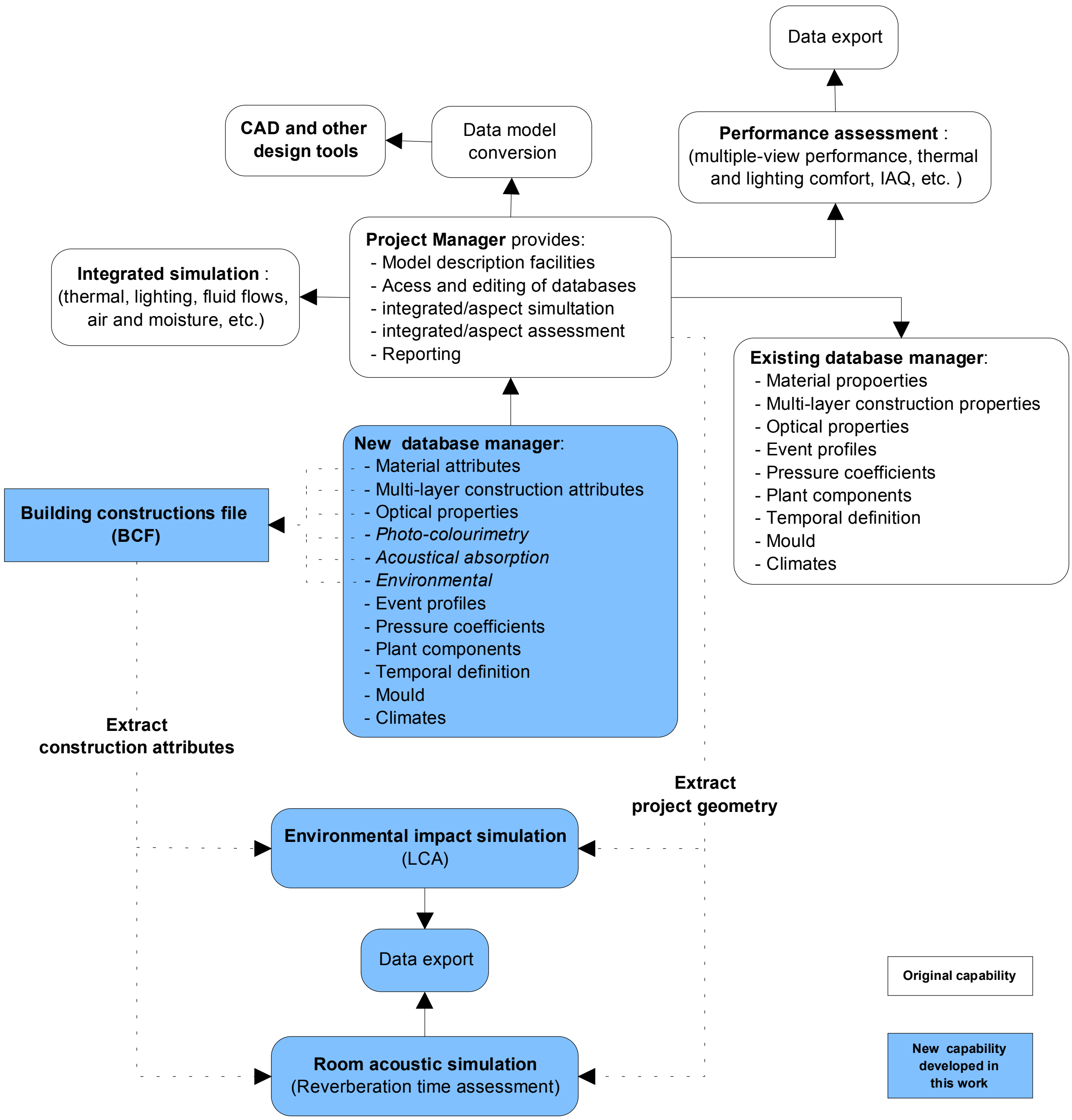


Figure 4.19 ESP-r suite with temporary developments in dot line. (ESP-r suite+.flo)

To encompass all the views required by a holistic simulation, the database manager maps the physical data model presented in this chapter. The assessment of the environmental impact and the room acoustic views is performed in separate modules. Each of them extracts the geometry information via the Project Manager and the physical information from the new database manager.

4.20 DATABASE SCHEMA

The database manager is the link between the application program and the database, whose purpose is to manage the information defined within the abstract representation of the data model. Database research underpins advances to provide accessibility to a large amount of information (its roots are related to the Apollo moon-landing project in the 60's [Con1996]). Nowadays, the market provides many database management systems (DBMS). These commercial products have been developed to assist the creation and use of other applications, and are tailored to be generic and user-friendly to satisfy a maximum of people. The whole point is to allow users, especially end users, to create a database without having to write lines of code in a conventional programming language.
The user-friendliness provided by these commercial databases is counterbalanced by their lack of flexibility, which is due to an effort to make the system more efficient. Most of the features proposed in commercial products are furthermore not necessary here and the products have the disadvantage of being bound to a particular product with all the problems that can entail for distribution and future development. Being independent of any commercial application requires more initial development, but eases future developments. Consequently it was decided for this work, to develop an internal database tailored to the model developed here. This guarantees the complete independence of ESP-r from any commercial applications.

Many database schemas exist, the most popular among which are the relational and the object-oriented approaches. To select the solution that is the most appropriate for the data model implementation, it was necessary to analyse and compare their capabilities. The relational DBMS is a widely used method that holds a collection of distinct relations, which can be seen as a collection of data recorded in a table (see Appendix H for the terminology). The relational schema popularity is related to the correspondence with the notion of a table, a simple graphical representation, and a rigorous mathematical foundation [Ull1989].

More recently, object-oriented DBMS have been gaining importance. The basic principle of object-oriented (O-O) schema is to reduce the considered problem to elementary objects and to group into classes the objects with similar properties. This approach has been developed to support features like inheritance, which enable an object of a certain class to inherit attributes of the higher-level class, a feature not supported by the relational model. A good overview of the available technologies for database implementation can be found in [Con1996; Dat2000] and more specifically for building simulation in [Ric1994]

It may be convenient to represent a building element as composed of several parts, which in turn are composed of other parts, and so on. The relational schema seems to be suitable for this cascade representation and the O-O approach seems more appropriate to model the building in a recursive way. The inheritance principle has promoted the selection of the O-O schema for modelling a building and has been widely used since the end of the 80's. Nonetheless, there is no standardised classification of building elements and arbitrary decisions made during the class and hierarchy design can limit the use of the O-O approach [Wri1992]. The same building can be described using various object decompositions, which tie the object decomposition to the application. In addition, from this lack of hierarchy standardisation ensues that views using different object decompositions will not be able to directly communicate and exchange information. Finally, the rules for updating, modifying or extending an O-O model for a new view are specific to each approach used, which complicates the model's evolution [Eas1991].

The relational model requires data homogeneity. Each tuple (record) of a relation must be composed of the same attributes and the values of the same attribute must all come from the same domain and must be atomic. Although it may be too restrictive in some case, the data homogeneity requirement of the relational approach is not a limitation here. The physical data model proposed in this work is a structured volume of information with well-defined attribute types that fit the relational schema requirements. According to the requirements needed to support that information management and in the light of the previous considerations, the relational approach seems to be well adapted for the implementation of the proposed physical data model.

4.21 RELATIONAL SCHEMA

In general, different materials have different physical properties. For instance, the density of wood is different from the density of concrete. Even within a same material category, there are differences. The density of reinforced concrete changes according to the fraction of steel used. Theoretically, there is a one-to-one relationship between a material and its physical attributes and it would be possible to store the whole information in one table, in which a tuple would store all required physical properties. In reality, it may happen that different materials have similar physical properties. Let us consider reinforced concrete with two different steel frame fractions. Depending on the steel fraction, properties such as the environmental impacts are not similar for both variants. On the other hand, the steel fraction in the concrete does not affect the acoustic absorption at the concrete surface and in consequence both materials have the same set of coefficients.

It would be efficient to signify that both types of reinforced concrete use the same set of acoustic absorption coefficients while storing the set of coefficients only once. The relational schema composed of several relations enables storing the set of acoustic coefficients in a tuple in an *acoustic* relation and linking this information to several materials as schematised in Figure 4.20.

It may also happen that some physical properties are unknown for a particular material. For instance, assuming that the acoustic absorption coefficients for granite are unknown, it is acceptable in a first approximation to use those of another hard and rough material such as concrete. And when the coefficients for the granite are known, it is possible to populate the acoustic relation with a new tuple that holds the new coefficients and the relationship will then be updated to relate this new instance. As the set of coefficients exists only once, the value has to be updated only once and the modification is automatically ‘passed’ on to the related tuples in other relations.

To summarise, the relational schema is adapted to the construction data model, does not require any hierarchical classification and permits to reduce the complexity of the data management system, to avoid any redundancy and to take into account the practice limitations on available information.

Material relation	…	Room acoustic	Hygrothermal	LCA manufacturing	…
…	…	…	…	…	…
Cellular glass	…	CellGlass	HCell_glass	MCelGlass	…
…	…	…	…	…	…
Granite	…	RoughCon	HGranite	MGranite	…
…	…	…	…	…	…
Rienforced concrete for facade	…	RoughCon	HConc_fac	MRienConF	…
Rienforced concrete for slab	…	RoughCon	HConc_slab	MRienConS	…
…	…	…	…	…	…

Room acoustics relation	Primary key	Frequency [Hz] 100	125	160	200	250	…
…	…	…	…	…	…	…	…
Cellular glass	*CellGlass*	0.03	0.04	0.05	0.05	0.06	…
Concrete (rough)	*RoughCon*	0.01	0.01	0.01	0.01	0.01	…
Curtain (light)	*LightCurt*	0.02	0.04	0.10	0.17	0.23	…
…	…	…	…	…	…	…	…

Hygrothermal relation	Primary key	Conduct. [W/(mK)]	Density [kg/m³]	Vapor resist. -	Emissi. -	Solar absor. -	…
…	…	…	…	…	…	…	…
Cellular glass	*HCell_glass*	0.05	120	75'000	0.96	0.88	…
…	…	…	…	…	…	…	…
Granite	*HGranite*	3.50	2'800	10'000	0.90	0.55	…
…	…	…	…	…	…	…	…
Reinforced concrete for facade	*HConc_fac*	2.50	2'400	120	0.93	0.65	…
Reinforced concrete for slab	*HConc_slab*	2.30	2'300	120	0.93	0.65	…
…	…	…	…	…	…	…	…

Manufacuring environ. impacts relation	Primary key	NRE [MJ]	GWP [kg CO2-eq.]	AP [kg SOx-eq.]	POCP [kg C2H4-eq.+ NOx]	…
…	…	…	…	…	…	…
Cellular glass	*MCelGlass*	6.213E+01	2.622E+00	2.078E-02	1.179E-02	…
…	…	…	…	…	…	…
Granite	*MGranite*	2.153E-01	1.291E-02	6.910E-05	2.744E-05	…
…	…	…	…	…	…	…
Rienforced concrete for facade	*MRienConF*	1.769E+00	1.670E-01	6.520E-04	6.520E-04	…
Rienforced concrete for slab	*MRienConS*	1.400E+00	1.570E-01	5.780E-04	5.780E-04	…
…	…	…	…	…	…	…

Figure 4.20 An example of a relational schema. (relational example.dsf)

The definition of the physical attributes of a material in the database obeys to the following procedure: (1) Definition of the physical attributes for a particular view (hygro-thermal, acoustics, etc.) and (2) link of this set of attributes with a particular material. To illustrate this procedure, the assignment of acoustic absorption coefficients for reinforced concrete is presented in Figure 4.21.

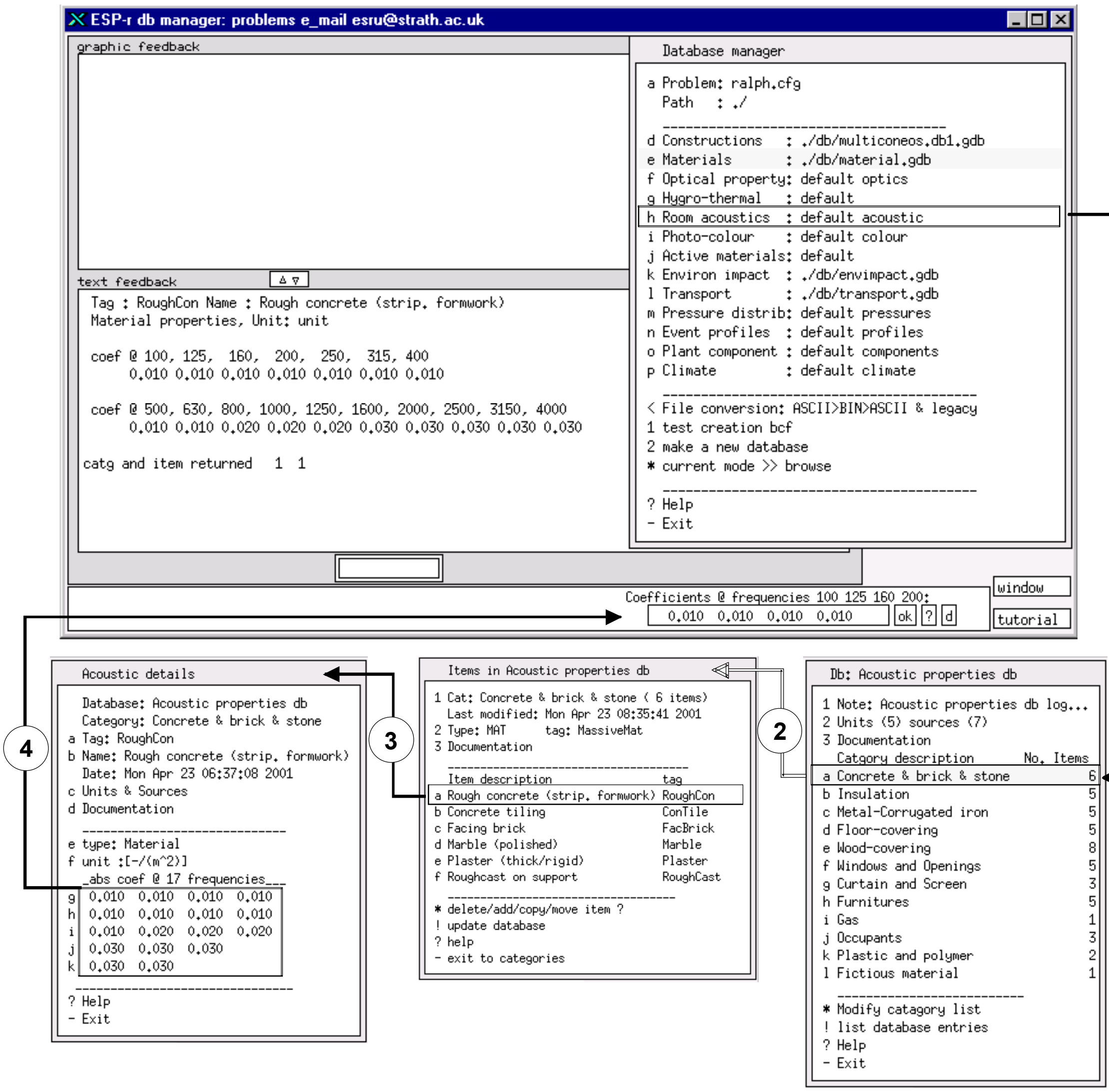


Figure 4.21 Selection procedure to define a set of acoustic absorption coefficients. (Acoustics attributes.dsf)

The top part of Figure 4.21 shows the interface of the ESP-r database manager. The main menu (right) lists all the available relations, among which the *Room acoustics* item must be selected to display the list of available acoustic categories (① in Figure 4.21). These categories have been defined to help the classifying of the records in a meaningful order, but can be modified (rename, add new and delete) if necessary. The selection of the *Concrete & brick & stone* displays the list of sets recorded in that category (②). The items stored in a category can be modified by the addition of new items and the data of an existing item can be modified. For instance, if the *Rough concrete* item is selected (③), it is possible to change the corresponding acoustic absorption coefficients from the menu that displays the acoustics details of that set (④).
The previous procedure defines only a set of physical attributes for a particular item (here *Rough concrete*) for a particular view (here *Room acoustics*). It does not define to which material this set

corresponds. The next step consists in linking this set of attributes to a particular material itemised in the *Material* database.

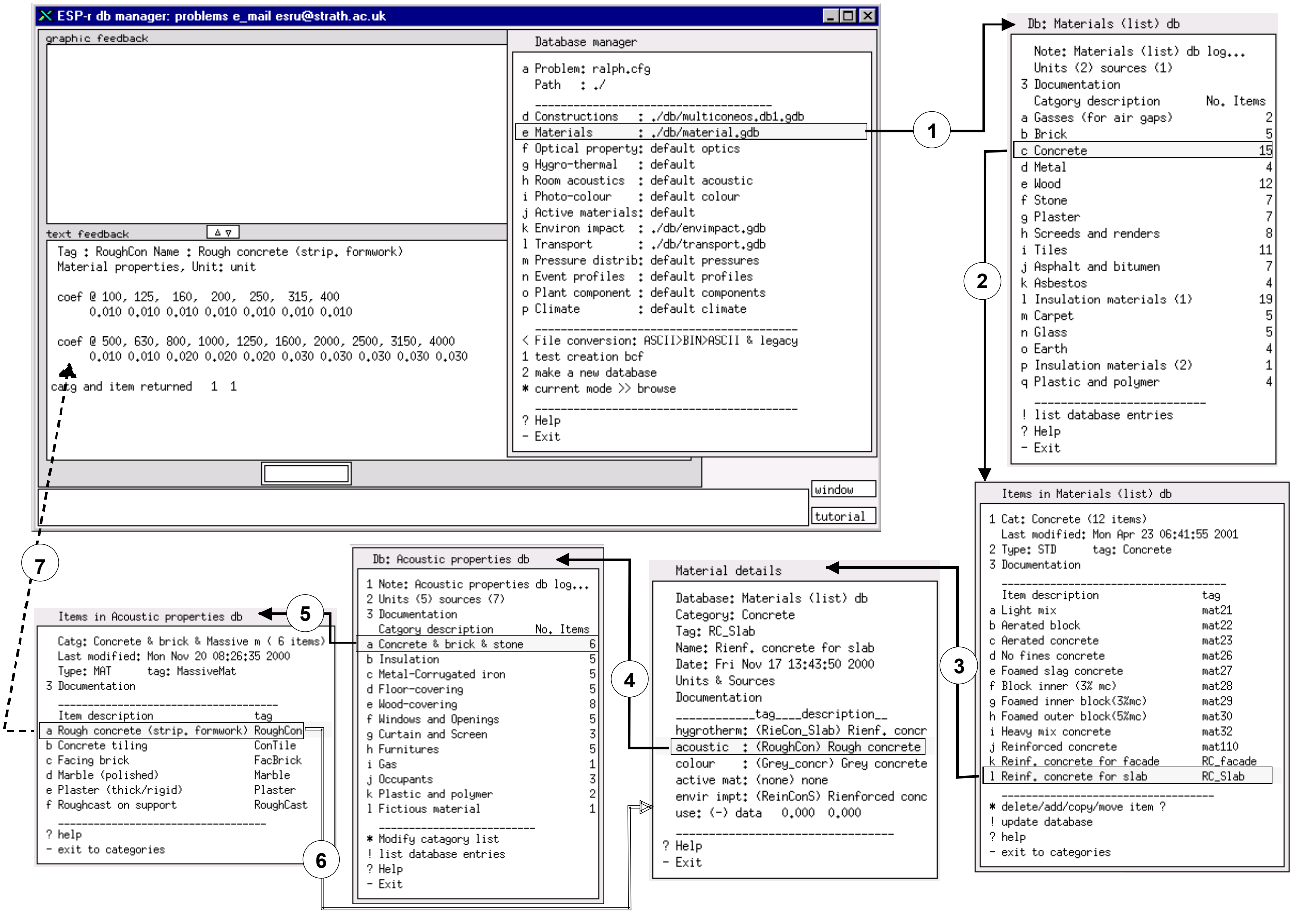


Figure 4.22 Selection procedure to define the acoustic absorption coefficients set for a material. (material.dsf)

Figure 4.22 shows the procedure required to link the set of acoustics attributes defined previously to a material (based on the example used in Figure 4.21). In this example, two qualities of reinforced concrete are itemised in the corresponding material database: (1) for Facades (*Reinforced concrete for facade)* and (2) for Slabs (*Reinforced concrete for the slab*). Although most of the physical attributes are the same for both qualities of reinforced concrete, the distinction has been made, because they do not have the same environmental impacts due to the different amounts of steel used for the framework. From the main menu of the database manager, select the Materials database (① in Figure 4.22), which replaces the main menu by the list of available material categories. In selecting the *Concrete* category (②), the menu lists the available qualities of concrete. The selection (③) of the *Reinforced concrete for slab* shows the pointer name for each view (hygro-thermal, acoustic, etc.). The selection of the *acoustics* item (④) in the *Material details* menu allows modifying the set of physical attributes corresponding to the room acoustics view. The selection of this item loads the acoustic database and displays the categories that have been defined in it (see Figure 4.21). In the category *Concrete & Brick & Stone* (⑤), the item *Rough concrete* should be selected (⑥) to link the appropriate set of acoustic absorption coefficients to the *Reinforced concrete for slab*. In parallel, the data corresponding to the selected set of coefficients is displayed in the text feedback of the ESP-r interface (⑦).

4.22 BUILDING CONSTRUCTION FILE

On invocation of a view assessment such as a room acoustic or environmental assessment, the database manager generates a project-level file, named the *building construction file* (BCF), to assist the exploitation of the physical information. When construction attributes are required, the BCF is scanned to extract the information necessary for a particular view.
A parameter-passing convention has been adopted, wherein the properties of the materials and the construction itemised in a particular project are extracted from the database and translated into an ASCII file. The BCF file is composed of an iterative structure made of information blocks as shown in Figure 4.23.

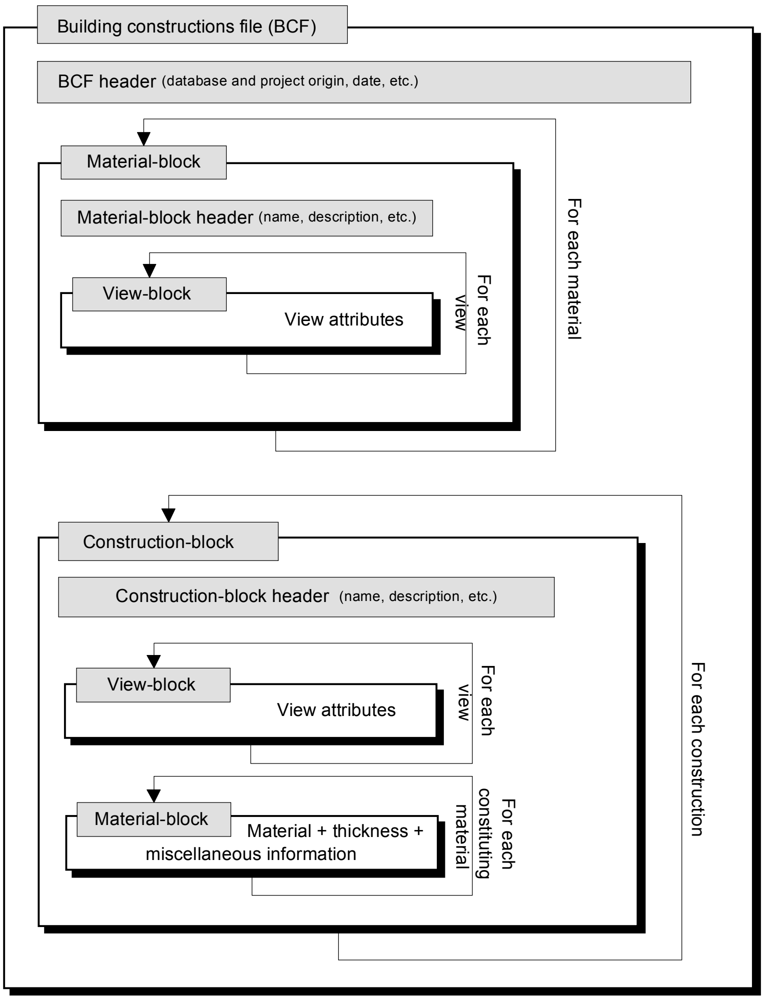


Figure 4.23 Building construction file (BCF) structure. (BCF structure.flo)

The BCF is composed of two main blocks that describe material-level and construction-level information. The former block is constituted of a list of itemised materials within the constructions of the project. Each material block holds the physical attributes for the different views. The second main block holds the information at the construction level, plus the list of materials that constitute the construction. The interested reader can find a detailed description of the BCF format in Appendix I.

CHAPTER 5

LIFE CYCLE IMPACT ASSESSMENT OF A BUILDING

The goal of this chapter is to present the first new view implemented in ESP-r to extend its capabilities. The proposed approach is based on the life cycle assessment framework proposed by the International Organisation for Standardisation (ISO) for the assessment of the environmental impacts of a product. This view enables a detailed assessment of the potential environmental impacts[4] generated by a building during its entire life span, from cradle to grave.
To take account of all impacts, a global balance of materials and energy flows required during the building life has to be established. The presented methodology focuses not only on the impacts related to material manufacturing, but also on those generated during the transport, assembly, maintenance, replacement and final disposal of the materials at the end of the building life. At the end of the impact assessment, the results are expressed as a set of environmental indicators that have been selected among the inventory loads and environmental effects obtained with a multiple-step impact assessment method.

5.1 INTRODUCTION

In 1930, ozone depletion and global warming were probably not the main concerns of Thomas Midgely, Jr. at the DuPont Co. when he combined chlorine, fluorine, and carbon to produce a new generation of *nontoxic* synthetic refrigerants for commercial use that were sold under the trade name Freon. All began to change in 1974, when scientists realised that the chlorine atoms of these chlorofluorocarbons (CFCs) could wreak havoc on the sparse layer of ozone molecules that filters out much of the sun's harmful ultraviolet rays. But it failed to get much attention until 1985, when an alarming 'hole' in the ozone layer over Antarctica was discovered. Even if the cause of this hole is still debated, by January 1996, the production of CFCs was banned in industrialised countries [Mal1997].

More generally, the environmental limits to human activities in a finite world have been debated since the 1960s [Car1962; Mea1972], but wide public awareness was only really brought along by the oil shocks in the 70s, which forced national governments to define energy consumption limits to reduce their dependence on oil as a non-renewable energy source. Twenty years later, the

[4] The term *impact* means any modification of the initial environment due to a human intervention.

environmental impacts due to human activities are again gaining public and political awareness, especially due the warming up of the atmosphere temperature.
Protection of the environment is one of today's key issues, that generates a wide range of initiatives world-wide, such as the publication of strategic documents to promote sustainable development or the much publicised intergovernmental ‘Earth Summit’ conferences in Rio de Janeiro in 1992, Kyoto in 1997 and The Hague in 2000, where international agreements on environmental issues, such as the reduction of CO_2 emissions, were negotiated.
In this framework, governments have stimulated interest in the study of the environmental implication of building construction. There is also a demand for sustainable buildings from some investors and architects. For instance, Sir Richard Rogers has integrated the concept of sustainable development into the master plan of the Potsdamer Platz reconstruction in Berlin, including waste recycling, water and energy management. These principles have been applied by Renzo Piano for the Daimler-Benz building [A&T1993].

Although there are no official standards, a global environmental impact assessment of a building can and should be performed. This assessment is a meticulous task that has to account for all the contributions of all the materials and processes used within and for the building. Whereas there were about 50 different materials at the turn of the previous century, there are nowadays more like 50'000 [Fos1997], which complicates the matter. This is why it is necessary to provide automated tools with adequate methods to simplify the environmental impacts assessment of a building.

5.2 ENVIRONMENTAL IMPACTS OF BUILDINGS

The early design stage of a building, when the site, orientation, and shape are selected and the envelope is defined, will influence the heat losses, the daylight and passive solar availability. Decisions taken at that stage, therefore directly influence the amount of energy that will be consumed by the building services. At the end of the 90's, it was estimated that the energy consumed by buildings during their utilisation phase (heating, ventilation, lighting, etc.) amounted to more than 50% of the UK [Har1997] and the Swiss [SIA1998b], and 35% of the Norwegian [Fos1997] national energy consumption. A similar proportion of the carbon dioxide (CO_2) emissions, which have a major impact on the global warming of the atmosphere, can be attributed to the building sector as well. Technical developments and political decisions have already helped to reduce the energy consumption by one quarter during the last decade in Switzerland and it can be hoped that the tendency will carry on in the future.

Energy consumed for building operation is not the only hazard a building creates to the environment. The construction materials and processes used during the building life span also have to be considered conscientiously. For instance, the processing of the refined ore into a construction material requires energy input and the process itself may have environmental side effects such as pollutant emissions or waste production. Since the 70's, several authors have analysed the environmental impacts of materials and services related to the building industry. Chapman [Cha1975] and Baird [Bai1983] were among the first to stress the importance of taking into account building materials and processes over the whole life time of a building and to estimate the inevitable environmental impacts due to the construction processes.

In fact, any phase of a building lifetime may generate environmental impacts. The energy necessary to produce construction materials used in the UK is estimated at 25% (350 PJ/year) of the annual energy consumption in the domestic sector and is responsible for 10% of the carbon dioxide emissions [And2000; Wes1994]. At the end of its life, a building also generates material waste flows, which must be included in the assessment of the environmental impacts of a building. Building activities generate each year about 3.5 million tonnes of waste in Norway [Fos1997] and about 7.1 millions tonnes in Switzerland [PI-BAT1992], which represent approximately 10% of the input construction materials. This waste generates environmental impacts during transport and processing. Although nowadays more and more of the construction waste is recycled, still about 67% of the approximately 70 million tonnes of construction and demolition waste produced each year in the UK end up in a landfill [Fre1997].

5.3 IMPACT ASSESSMENT METHODOLOGIES

While environmental modification seems inevitable as a result of human activities, its rate and extent estimation is a complex issue. Currently various solutions are available ranging from easy-to-use to complex and detailed methods. Eco-labelling or environmental guides for construction materials, such as given in [And2000; Ani1996; Sch1998; SIA1995a], offer simple support for a quick qualitative environmental assessment of construction materials. More sophisticated methods, such as the BREEAM (Building Research Establishment Environmental Assessment Method) method [Pri1993; Yat1997] developed in the UK or the BEPAC (Building Environmental Performance Assessment Criteria) method developed in Canada [BEPAC1993], enable a qualitative assessment at the early design stage. These qualitative methods aim to minimise the environmental impacts of the project, by allocating credits where satisfactory attention is paid to a list of criteria such as site, wind and sun exposure, envelope concept, materials, energy consumption and material used. They can readily be assessed and might be a satisfactory solution for the early design stage. For the interested reader, a comparison of different impact assessment methods can be found in [SIA1998a].

5.4 LIFE CYCLE ASSESSMENT

To enable a comprehensive and quantitative appraisal of the environmental effects of a building, it is necessary to turn towards sophisticated decision support methods. Among the different available approaches, the environmental Life Cycle Assessment (LCA) seems to be the most approved approach at the present time and has been retained as the general framework of the developments presented in this chapter.

The LCA is a method for analysing and assessing the environmental impact of a product (material or service) throughout its entire life cycle and is defined in the ISO standards 14040 to 14043 [ISO1997]. The LCA approach is based on the belief that all stages in the life cycle of a product generate environmental impacts and proceeds in the following steps:

1. *Goal definition* spells out the purpose of the study, its scope, and the time and spatial resolution. It also includes the description of the system boundaries, its level of detail and the origin of the collected information. The result of this step is a clear, accurate and transparent description of the analysed system.

2. *Inventory analysis* identifies and quantifies the environmental loads associated with the product, such as resources depletion (material and energy) or pollutant emissions. It inventories the discharge of chemical or physical loads (substances, heat, noise, etc.) from the product system to the environment. The inventory analysis results in an *inventory table* that lists all itemised loads.

3. *Life cycle impact assessment* defines and quantifies all potentially adverse effects of a product based on the inventory analysis. It includes their classification into impact categories and the evaluation of the characterisation factors, which weight the effect of the inventoried loads for each category. Then it combines the loads listed in the inventory table for each environmental category (characterisation).

4. *Results interpretation* analyses the environmental impacts in accordance with the goal of the LCA study and may include an improvement analysis. Result interpretation based on these environmental indicators may provide a starting point for the redesign of a building.

Although the ISO gives entire liberty as to the methodology used during the life cycle impact assessment step (LCIA), it must be clearly defined and adapted to the scope of the study. Among the various available solutions, an impact assessment method has been selected from which several environmental indicators are extracted to provide the environmental profile of the building.

It is important to note that the LCIA as developed by the ISO is normally applied to a single product. A building is a complex object, made of a variety of materials with different life service that require various services during the building's lifetime. According to Edwards [Edw1998] «*there is a need for an applied life cycle assessment process capable to include different materials with varied lives and applications, coming from a variety of sources and processes*». Thus, to be exhaustive, the LCIA of a building must be analysed at the building level and the system boundaries should include all the materials and processes that occur during the different phases of the buildings' life-cycle and that have a potential effect on the environment.

5.5 SYSTEM BOUNDARIES

For an LCA to be exhaustive, the system boundaries should encompass all energy and mass flows related to the analysed product. For instance, the material transport requires energy to move the vehicle. To be exhaustive, it should also include the flows generated by the vehicle construction, the energy to cook the driver's meal, etc. If extended, this analysis might include the whole world. Fortunately, the system can be limited to pertinent mass and energy flows and neglects those that do not represent a relevant contribution to the system. It is, however, not sufficient to analyse the negligibility of a flow only with one of those criteria.

Even if the mass of an element can be neglected with respect to the mass of the whole analysed product, it may be very important from the environmental point of view. For instance, Adalberth [Ada1996] shows that a weight of plastic that corresponds to approximately 2% of the whole construction, and the weight of concrete, which corresponds to about 70%, may each account for about 20% of the energy required to manufacture the construction materials. In other words, the pattern of material weight proportions may be very different from the pattern of the environmental impacts. Thus, to be excluded from the LCIA, a flow must have a negligible contribution with regard to the total flows following the three criteria of mass, energy and environmental impact.

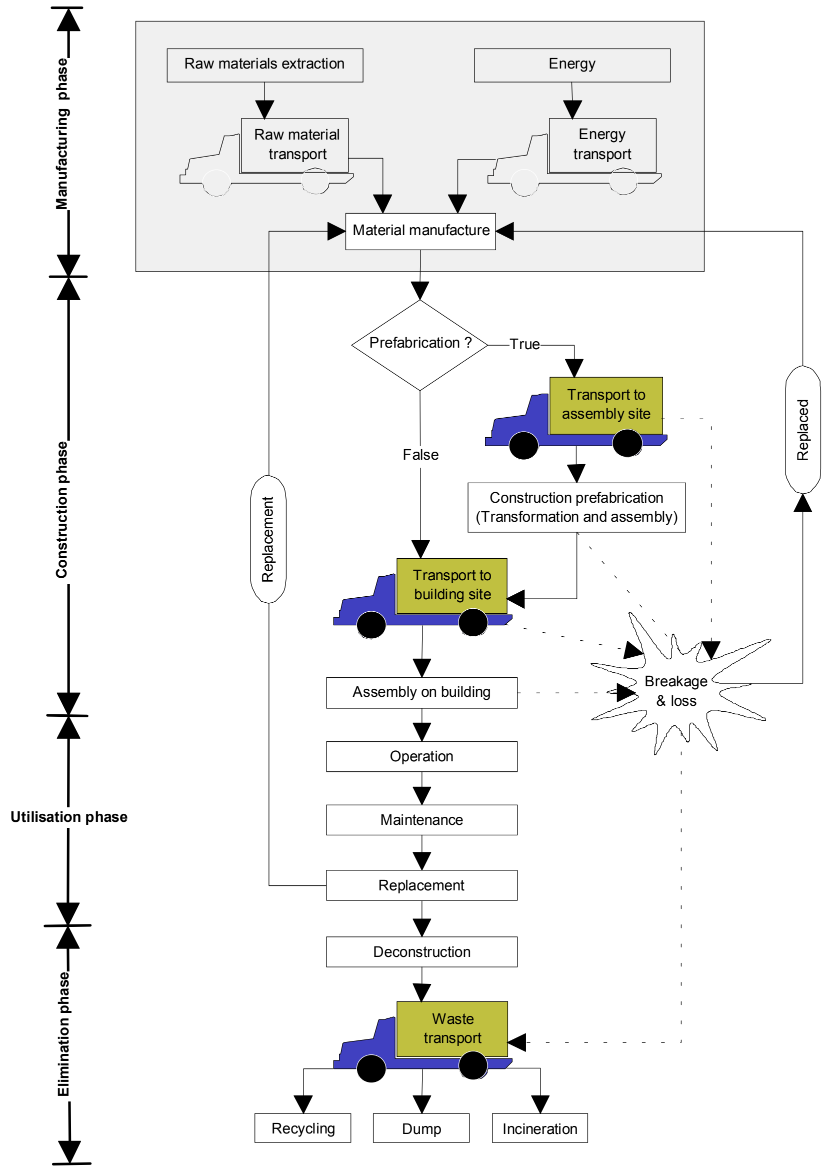


Figure 5.1 System boundaries for the building LCIA. (boundaries very little.flo)

Among the different flows that occur during the construction of a building, Blouet [Blo1995] shows that the following can be neglected:

- Human activity, which generates two sub-flows: food and people transport; both of which can be neglected. For most industrial processes, only a few people are involved in the production phase. Furthermore, most of the energy consumed by a human body is used to supply its vital functions and therefore, the human activity contribution to an LCIA can be neglected.
- Transport infrastructure: To bring down transportation to its elementary flows leads to considering the infrastructure. For instance, for road transportation, the asphalt and the road roller that spread it could be included. But the infrastructure is used not only for the considered product transportation. Spread over all transported goods and people, the flows required to construct the transportation infrastructure can be neglected regarding the LCIA of the analysed product.

Although the transport infrastructure can be neglected, the energy required for the transportation process is a flow that cannot be neglected. For instance, Miller [Mil1997] estimates that transportation energy represents approximately 6% of the energy required to manufacture, transport and assemble a material. And this value can be double if the return journey of the transport is taken into account[5]. As pointed out by Baisnée [Bai1994], the environmental impacts generated by the transport phase should be carefully analysed and modelled, taking into account characteristics such as the truck loads, delivery and return journey, product losses and damage during transportation.
According to these considerations, the system boundaries used in this work include the environmental impacts generated by the manufacturing, transport, assembly, operation, maintenance and replacement, decommissioning and elimination of the construction materials used in the building, as shown in Figure 5.1. To be exhaustive, the system limits also encompass the material lost and broken during transport and assembly processes

The environmental impacts generated by raw material extraction, transport and processing are merged into the manufacturing phase (the greyish rectangle in Figure 5.1). This is mostly due to the rare availability and the volatility of such information. Fortunately, the system boundaries traditionally used to perform the LCA of construction materials cover these different elementary phases, and therefore, these data can directly be used to represent the environmental impacts generated by material manufacturing.

5.6 ENVIRONMENTAL IMPACT INDICATORS

The assessment of the environmental impacts generated by a building requires the selection of environmental indicators among the variety of available metrics resulting from a LCA. At the inventory level, the indicators can be selected from the inventory table, which may include a large number of itemised loads. With the personal computer power available today, a large number of indicators is not a limitation. Nevertheless, several problems may emerge if the number of environmental indicators is too large. First, it may be difficult to keep the information up to date due to the quantity of data. Second, different products may generate different impact types. This heterogeneity of the inventoried impacts may complicate inter-comparison of variants. And even if the same loads are generated, an excessive number of indicators may complicate the comparison of alternatives, even if they could be listed according to their severity, such as the priority method proposed by Schmidt [Sch1992]. A logical simplification is to aggregate the inventoried impacts by specifying their contribution, based on scientific analysis, into a reduced number of environmental problems. The major advantage of such a valuation approach is to simplify the result communication, which in turn may simplify the final decision between alternative solutions. The valuation methods currently available can be separated into the following two categories:

- *Single-step*, in which the inventoried impacts are aggregated into one overall index in one step, such as the Swiss Ecopoints [OFE1991] or the Swedish EPS [Ste1999]. Single-step assessment methods do not explicitly characterise the impacts before completely aggregated scores are calculated. This lack of self-contained transparency of the data may complicate the result interpretation.
- *Multiple-step*, in which the inventoried impacts are aggregated into a higher level index in more than one step such as the Swiss Critical Volume [BUW1984] and Critical Surface-Time'95 [Jol1997] and the Eco-indicator'99 [Goe1999].

[5] For the building analysed in the same study, the transportation of ready-mix concrete and of the structural steel beams represents about 11% and 17% respectively of the total transportation energy of the materials.

Currently, there is a lively debate around these aggregation methodologies developed for the impact assessment. It is out of the scope of this work to debate these methodologies. Nevertheless, one method had to be selected to demonstrate the applicability of the developments undertaken to assessing the environmental impacts of the building. The ISO standard does not specify which methodology is to be used during the impact assessment step, but the multiple-step approach is nevertheless preferred as it keeps the transparency of the results obtained during the different steps of the impact assessment and eases result interpretation.

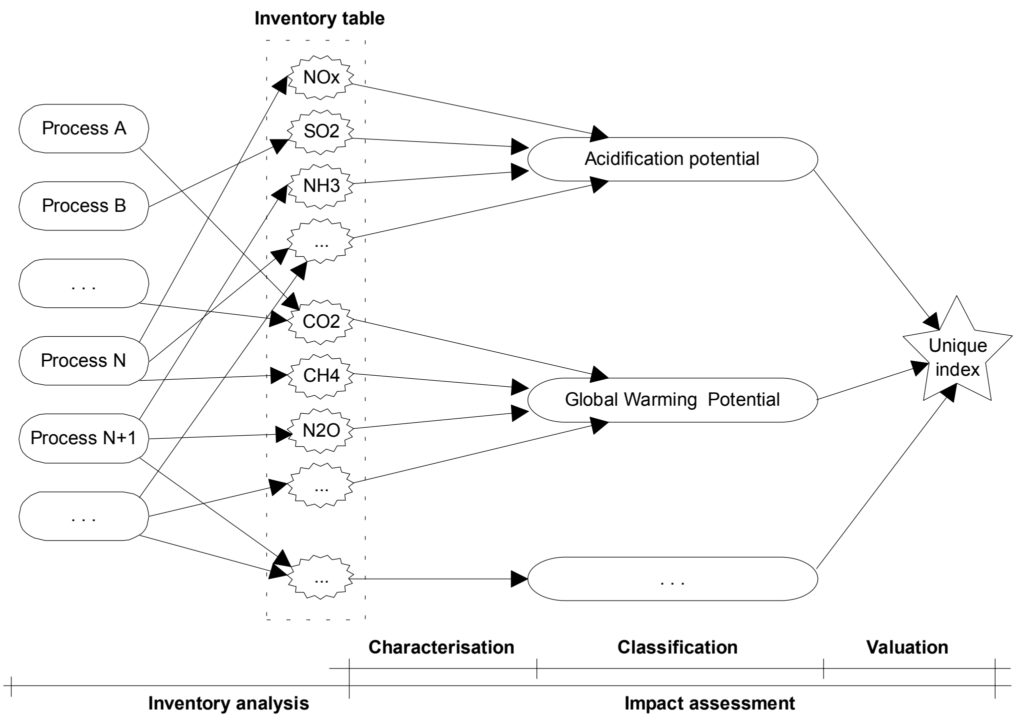


Figure 5.2 Example of a multiple-step impact assessment approach. (LCA steps.flo)

The ISO standard 14040 [ISO1997] proposed an impact assessment made of the following steps, which are shown in Figure 5.2.

- *The classification* defines the set of potential environmental effects that may follow from the loads obtained in the inventory table during the inventory analysis.
- *The characterisation* permits giving a weighting factor, named characterisation factor, to aggregate the loads according to its influence on a particular category defined in the classification step. The characterisation factors enable the aggregation of the inventory table into environmental effect scores for the category defined in the classification step and results in a set of effect scores that together form an environmental profile (sometimes referred to as the eco-profile).
- *The valuation* combines the environmental effects obtained in the characterisation step, in order to achieve a single environmental index. The goal of the valuation is to simplify the comparison between variants.

The valuation step may simplify the comparison between variants. But currently, most of the impact assessment approaches are still under development and evolve rapidly, so for the moment, there is no recognised final approach. As there is no single valuation methodology that is accepted worldwide, no valuation index has been retained here as a possible environmental indicator. The previous considerations have led to the decision to extract the environmental indicators from the set of environmental effects obtained upstream of the valuation step.

Although there is no worldwide-accepted approach, the characterisation factors proposed by Heijungs [Hei1992] in the CML[6] method achieve a good agreement in the scientific community. They have already been used as basis for different valuation methods and are used in several applications such as Regener [Peu1997], Eco-Quantum [Mak1997] and OGIP [Koh1996]. The Appendix J summarises the features of the CML methodology, which proposed a classification into fourteen environmental effects, among which some may not be relevant for the building industry, as for instance the number of victims. In accordance with others [Eye2000; Tru1997], the following indicators have been retained from the CML classification as relevant for the building LCIA:

- Global Warming Potential over a 100 year period (GWP100)
- Acidification Potential (AP)
- Photochemical Ozone Creation Potential (POCP)

These environmental effects will be used as the first three environmental indicators. In addition, one other metric value, provided by the inventory analysis step, has been retained because it is often referred to in the literature:

- Non-Renewable Energy (NRE). Energy use is converted from delivered to primary energy and then only the energy obtained from non-renewable sources is taken into account.

To be consistent with the physical data model defined in the previous chapter, the environmental cost attributes can now be expressed for each selected indicator as shown in Figure 5.3. It displays only the four retained environmental indicators; nevertheless, the data model allows the storage of up to ten indicators, a number that, if not sufficient, can be easily increased.

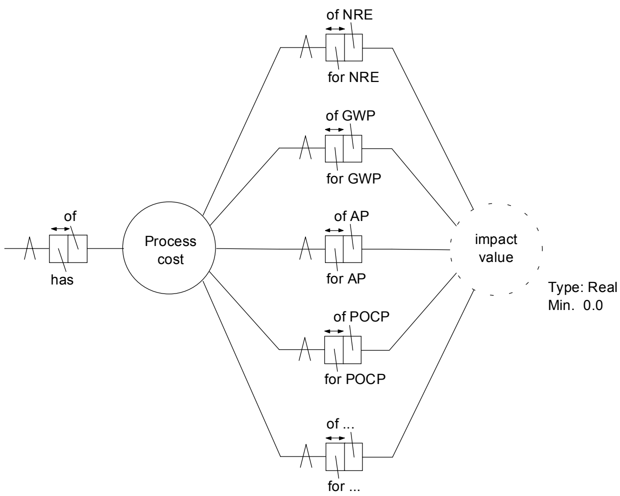


Figure 5.3 Conceptual representation of the environmental impacts. (impacts.flo)

[6] Dutch abbreviation for Center of Environmental Science (part of Leiden University, the Netherlands)

These indicators are related to the global external environment. However, a part of the environmental problems related to the building sector might arise locally in connection with the indoor environment, like for example the human toxicity indicator. Compared to the selected impacts, there is not yet a consensus among the developers of the LCIA methodology regarding the weighting factors defined in the characterisation step for some emissions influencing human health, such as for VOCs [Jön1998], and therefore, they have not been considered here.

5.7 ENVIRONMENTAL DATA ORIGIN

The environmental data used in this work come from recognised and public sources that provide information related to the manufacturing of construction materials, transports and construction processes, and energy consumed for services. At present, the data set ECOINVENTARE [Sut1996] of the Swiss Federal Institute of Technology (ETHZ/ESU) is the most complete source of data according to the European Commission [REG1997]. Nevertheless, it does not provide sufficient information to perform a comprehensive LCIA and the additional sources listed in Table 5.1 were used.

Depending on the purpose of the study, the sources may have defined a different system boundary than used in this work. To keep the consistency with the approach presented here, the information of such a study can be used but with caution. It has to be dissected to extract specific information such as the means of transport used, the distance covered during the different transportation phases, the rate of material lost during a specific phase, etc. But this is only possible as long as the study clearly defines the system boundaries and the hypothesis used.

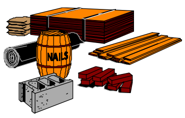
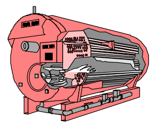
Source	Materials manufacturing 	Transport 	Energy 	Processes 
Weibel [Wei1995]	✓			
D0123 [SIA1995a]	✓			
Rentz [Ren1998]				✓
Richter [Ric1996]	✓	✓		
Eyerer [Eye2000]	✓		✓	✓
Ecoinventare [Sut1996]	✓	✓	✓	✓

Table 5.1 Origin and covered domains of the environmental database used in this work (✓: included).

The indicators (NRE, GWP, POCP and AP) used in this work were selected to demonstrate the feasibility of the proposed approach, but the developments presented in this document to assess the LCIA are independent of the selected indicators. Other indicators such as EPS or Eco-Indicator'99 could be used as well and it is even possible to store a set of mixed indicators extracted from different impact assessment methods. For instance, Figure 5.4. shows the principle of a record

which stores impact factors resulting from the inventory step (NRE), from the characterisation step (CML) and from the valuation step (Ecoindicator-99, EPS and Ecopoints), expressed in the corresponding unit. The results obtained with this mixture of indicators cannot be directly compared. Nevertheless, such a record enables the comparison of relative results, which permits an analysis of the implication of the hypothesis used in these different methods as proposed by Jönsson [Jön2000].
To keep the presented approach independent of the data set origin, the term *impact factor*, abbreviated *IF*, is used in the remainder of this chapter as a generic designation of the value stored in the database independently of the indicator used.

	Inventory	Characterisation step		Valuation step			
	↓	↓	↓	↓	↓	↓	
Product x	NRE	GWP	AP	Eco-indicator'99	EPS	Ecopoints	…

Figure 5.4 Example of a record that mixes environmental impact factors obtained with different assessment methods.

5.8 ENVIRONMENTAL IMPACTS ASSESSMENT OF THE BUILDING

The environmental impact generated during the building life span encompasses two contributions:

- **Intrinsic**, which includes all the mass and energy flows required by the building elements to exist as a physical entity during the building life span.

- **Extrinsic**, which corresponds to the energy consumed by services to provide an acceptable indoor climate for a certain function, such as for the heating, cooling, ventilation and artificial lighting. The extrinsic contribution is generated only during the building operation phase.

The total environmental impacts l generated during the building life span is then the sum of the intrinsic and extrinsic contribution and is given by

$$EI_l^{Building} = EI_l^{Extrinsic} + EI_l^{Intrinsic} \tag{5.1}$$

where

$EI_l^{Extrinsic}$ Environmental impact l generated by the extrinsic contribution, in the unit of the corresponding impact [Impact]

$EI_l^{Intrinsic}$ Environmental impacts l generated by the intrinsic contribution, in the unit of the corresponding impact [Impact]

Both contributions are appraised separately. The extrinsic impacts are determined from the assessment of the building performance, while the intrinsic impacts are determined from a detailed analysis of all intrinsic contributions.

5.9 EXTRINSIC ENVIRONMENTAL IMPACTS

The extrinsic impact l due to the energy consumed during the building lifetime is given by:

$$EI_l^{Extrinsic} = BLS \cdot \sum_s \left(E_s \cdot IF_{s,l}^{Energy} \right) \tag{5.2}$$

where

BLS	Building life span [y]
E_s	Annual energy consumed of fuel type s [MJ/y]
$IF_{s,l}^{Energy}$	Impact factor l of energy fuel s [Impact/MJ]

The annual energy consumption E_s is determined from the assessment of the building's annual energy consumption and is converted into environmental impacts according to the energy fuel used. Finally, the total extrinsic environmental impact generated during building operation is extrapolated over the building lifetime.

Table 5.2 lists the impact factors of two different energy sources. For electricity, the $IF_{s,l}^{Energy}$ differentiates between average European production, based on the UCPTE-mix, and Swiss (CH) production.

Fuel	Remark	Impact factors			
		NRE [MJ/MJ]	GWP [g CO2-eq./MJ]	AP [g SOx-eq./MJ]	POCP [g NOx-eq./MJ]
Natural gas	< 100 kW	1.51	85.50	0.10	0.09
Electricity	UCPTE	3.56	168.10	1.20	0.24
	CH	1.75	11.00	0.08	0.02

Table 5.2 Impact factors for electricity and natural gas energy sources (Extracted from [Sut1996]).

The electricity mix has a major effect on the impact factors. As can be observed in Table 5.2, a factor of about sixteen exists between the GWP impact factor for UCPTE and CH electricity production. The origin of this large difference lies in the channels used for the electricity production, which may differ between countries as shown in Table 5.3. As the building industry market has widened its boundary to the whole of Western Europe, it is preferable to assess the extrinsic impact generated by the electricity consumption with the IF based on the UCPTE-mix.

Country	Energy production channel		
	Hydraulic [%]	Nuclear [%]	Thermal [%]
Switzerland	60.9	35.2	3.9
France	14.7	77.0	8.4
Italy	20.3	0.0	79.7
Belgium	1.9	57.8	40.3
UCPTE-mix	15.6	36.3	48.1

Table 5.3 Energy production channels for different West European countries in 1999 (source [UCPTE1999]).

5.10 INTRINSIC IMPACTS

The intrinsic environmental impacts include the contribution generated by the material and energy flows required during the building life span and is equal to the sum of the contribution generated by all building elements during the building life cycle phases and is given by:

Building : $$EI_l^{Intrinsic} = \sum_k^{phases} \sum_j^{elements} \left(EI_{j,l}^k \right) \quad (5.3)$$

where

$EI_{j,l}^k$ Environmental impact l generated by element j during phase k [Impact]

To improve the accuracy of the calculation, a building element has been separated into two distinct parts: (1) surface-related and (2) perimeter-related. This solution enables a better appraisal of an element, such as a window, for which the frame length depends on the window geometry. According to this distinction, the intrinsic environmental impact of a building element is given by:

Element : $$EI_{j,l}^k = {}^{Sur}\overline{EI}_{j,l}^k \cdot A_j + {}^{Per}\overline{EI}_{j,l}^k \cdot P_j \quad (5.4)$$

where

${}^{Sur}\overline{EI}_{j,l}^k$ Specific environmental impact l generated by the surface-related part of the construction j during life-cycle phase k, in unit of mass per square area [kg/m²]

${}^{Per}\overline{EI}_{j,l}^k$ Specific environmental impact l generated by the perimeter-related part of the construction j during life-cycle phase k, in unit of mass per length [kg/ml]

A_j Area of element j, in square metres [m²]

P_j Perimeter length of element j, in linear metres [ml]

The symbol $\overline{}$ expresses a specific environmental impact, either per unit of area for the surface-related part of the construction or per unit of length for the perimeter-related part of the construction. The following sections focus on the description of the specific environmental impacts ${}^{Sur}\overline{EI}^{k}_{j,l}$ and ${}^{Per}\overline{EI}^{k}_{j,l}$ for each life cycle phase, the calculation of which requires the specific weight of the different materials that constitute a construction.

5.10.1 Areal and linear mass

The areal mass ${}^{Sur}\overline{M_i}$ of a surface-related material i with a uniform thickness e_i is given by:

$$ {}^{Sur}\overline{M_i} = \rho_i \cdot e_i \tag{5.5}$$

where

ρ_i	Density of material i, in unit of mass per volume [kg/m³]
e_i	Material thickness, in unit of length [m]

and the total mass of the construction j made of several materials is therefore given by

$$ {}^{Sur}M_j = {}^{Sur}\overline{M_j} \cdot A_j = \sum_{i \in j} \left({}^{Sur}\overline{M_i} \right) \cdot A_j = \sum_{i \in j} \left(\rho_i \cdot e_i \right) \cdot A_j \tag{5.6}$$

where

A_j	Area of element j, in square metres [m²]

For materials that do not have a uniform thickness over the construction surface, such as nails, the mass cannot be assessed in the same manner. In that case, the solution is to consider the material as a uniform layer with an equivalent layer thickness, which is equal to the mass of material per surface area divided by its density.

The mass of the perimeter-related part of the construction j is given by:

$$ {}^{Per}M_j = {}^{Per}\overline{M_j} \cdot P_j = \sum_{i \in j} \left({}^{Per}\overline{M_i} \right) \cdot P_j \tag{5.7}$$

where

${}^{Per}\overline{M_i}$	Linear mass of a perimeter-related material i [kg/ml]
P_j	Perimeter length of element j, in linear metres [ml]

To improve the mass calculation of a window, it is preferable to differentiate between the frame and the spacer component. For the frame, the linear mass is on the whole independent of the glazing unit thickness; it is therefore convenient to use its linear mass. For a spacer, its linear mass depends on the gap between panes and therefore, it is more convenient to use its sectional mass. Thus, the linear mass of the material is given by:

$$
{}^{Per}\overline{M}_i = \begin{cases} \textbf{Frame :} & {}^{Lin}\overline{M}_i \\ \textbf{Spacer :} & {}^{Sec}\overline{M}_i \cdot e_i \end{cases} \tag{5.8}
$$

where

${}^{Lin}\overline{M}_i$	Linear mass of the frame [kg/ml]
${}^{Sec}\overline{M}_i$	Sectional mass of the spacer [kg/m/mm]
e_i	Spacer thickness [mm]

Some building elements can be very complex and are made of several materials as for instance a window. To be exhaustive, the construction description of the window should include not only the panes, but also all the constituent materials of the spacer and the frame, such as the shell and the desiccant of the spacer or the handle of the frame. The data model developed in this work enables such detailed definition of all these constituent materials at the material level. But, even if possible, this way of working may be painstaking and requires construction knowledge. To simplify the setting up of the model, while keeping a detailed and accurate representation of the building element, it might be more convenient to replace a complex element by a single composite-material that includes the impact of the different constituent materials.

5.11 COMPOSITE MATERIAL

The presented approach allows the replacement of several materials by a single *composite material* for which the impacts correspond to the sum of the impacts of each composite constituents. The advantage of this solution lies in the definition of a construction. When selecting a material to include in the construction, it does not need to have particular knowledge in frame and spacer construction. Furthermore, the composite material does not need to be recalculated each time and may be reused in other projects. In return, the material-level information is lost in that it does not permit distinguishing the specific impacts of the materials that constitute the composite.
Replacing a complex element with a composite material is also convenient when the geometry model does not include part of a building element. For instance a window can be represented as a surface, which might represent at the same time the transparent unit, the frame, the spacer. In order to perform an accurate assessment of the window impact, these different components can be included in the window construction without an explicit geometry definition. In that case, the composite material is added to the construction like any other material. The frame and the spacer mass can then be calculated without defining their geometry explicitly.

The solution of replacing several materials by one composite material requires an external performance of this calculation and, possibly, a detailed LCIA of the considered component. The specific environmental impact of a composite material must be calculated before it can be stored in the database. Appendix K illustrates how the spacer constituents can be replaced with a single composite material.

5.12 MASS FOR AN ELEMENTARY LIFE CYCLE PHASE

For a material, the manufactured mass may not be equal to the mass within a building element. The material losses that occur during the transport and assembly phases require the manufacturing of a supplementary quantity of material to compensate for the waste. The following methodology has been developed to take account of this supplementary mass.

Assuming that $\overline{M_i}$, is the mass of material i required within a construction. Before it is placed within the construction, the material has been subjected to one or several processes since its release from the manufacturing site. During each process a fraction of material may be lost which must be compensated for in order to deliver the required material mass $\overline{M_i}$ as shown in Figure 5.5.

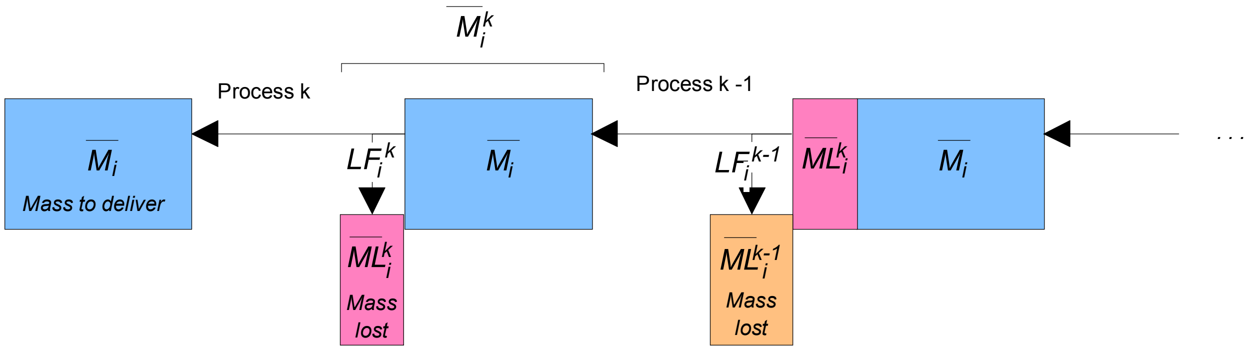


Figure 5.5 Assessment of the material losses occurring during material processes. (Mass lost.flo)

The material mass $\overline{ML_i^k}$ lost during the process k is given by :

$$\overline{ML_i^k} = \overline{M_i^k} \cdot LF_i^k \tag{5.9}$$

where

LF_i^k Fraction of material i lost during the process k [-]

$\overline{M_i^k}$ Mass of material i before the process k

According to the mass conservation law, the material mass $\overline{M_i^k}$ required upstream to the process k is given by the following mass equality:

$$\overline{M_i^k} = \overline{M_i} + \overline{ML_i^k} = \overline{M_i} + \overline{M_i^k} \cdot LF_i^k \;\Rightarrow\; \overline{M_i^k} = \frac{\overline{M_i}}{(1 - LF_i^k)} \tag{5.10}$$

If the previous mass equation is repeated for all the processes p upstream of the material delivering, the mass of material manufactured is given by [7]

$$\overline{M}_i^{Manufacture} = \frac{\overline{M_i}}{\prod_{p=1}^{k}(1 - LF_i^p)} \tag{5.11}$$

This equation is valid when the phases count in the reverse order of what occurs in reality. The mass flows during each life cycle phase can be calculated according to the previous equation.

Assuming that the mass of a material i within the construction is equal to $\overline{M_i}$. If this material is part of a prefabricated element, the mass transported from construction to building site with the n^{th} means of transport is given by

$$\overline{M}_{i,n}^{Cons \to Buil} = \frac{\overline{M_i}}{\prod_{t=n}^{m}(1 - LF_{i,t}^{Cons \to Buil})} \tag{5.12}$$

where

t	Means of transport identification
m	Maximum number of possible means of transport. In this work m = 3 for any transport phase)
$LF_{i,t}^{Cons \to Buil}$	Fraction of material i lost during the t^{th} transport ($t \leq m$) [-]

The fraction of material lost depends on the combination of the material type and the means of transport used. For instance, the fraction of glass lost during a journey by lorry may be different from that lost during a train journey. It should be remembered that the construction site is the location where the materials are assembled into a construction. For non-prefabricated elements, this mass flow is irrelevant.

The mass assembles at the construction site includes the material mass that has flowed through the assembly process. It should include the mass lost during the assembly process and the mass lost during the m different journeys from the assembly site to the building site for a pre-fabricated element. Thus the total mass assembly is given by

$$\overline{M}_i^{Assembly} = \frac{\overline{M_i}}{\left(\prod_{t=1}^{m}(1 - LF_{i,t}^{Cons \to Buil})\right) \cdot (1 - LF_i^{Assembly})} \tag{5.13}$$

where

$LF_i^{Assembly}$	Fraction of material i lost during the assembly process [-]

[7] The sign $\prod$ is the mathematical product.

Upstream of the assembly phase, the mass of material transported should include the material lost during the transport. For the n^{th} means of transport, the material transported from the manufacturing to the construction assembly site is given by

$$\overline{M}_{i,n}^{Man \to Cons} = \frac{\overline{M_i}}{\left(\prod_{t=1}^{m}(1 - LF_{i,t}^{Cons \to Buil})\right) \cdot (1 - LF_i^{Assembly}) \cdot \left(\prod_{t=n}^{m}(1 - LF_{i,t}^{Man \to Cons})\right)} \tag{5.14}$$

where

$LF_{i,t}^{Manuf \to Con}$ Fraction of material i lost during the t^{th} transport [-]

Finally, the manufactured mass of material i includes the losses during all the transport and assembly processes and is given by:

$$\overline{M}_i^{Manufacture} = \frac{\overline{M_i}}{\left(\prod_{t=1}^{m}(1 - LF_{i,t}^{Cons \to Buil})\right) \cdot (1 - LF_i^{Assemblage}) \cdot \left(\prod_{t=1}^{m}(1 - LF_{i,t}^{Man \to Cons})\right)} \tag{5.15}$$

Knowing the mass of material, it is possible to assess the contribution of each process during the building life span. The model proposed in this work to assess the environmental impacts generated during the building life span is detailed by the life cycle phase in the following paragraphs:

Elementary phases	Paragraph	Page
• Material manufacture (includes raw material extraction, process and transport)	5.13	90
• Transport to construction site	5.14	90
• Construction assembly	5.15	91
• Transport to building site (prefabricated)	5.16	92
• Placement on building (prefabricated)	5.17	92
• Maintenance	5.18	93
• Replacement	5.19	94
• Deconstruction	5.20	96
• Transport to disposal site	5.21	96
• Disposal management	5.22	97

Table 5.4 Location of the environmental impacts assessment for each life cycle phase

5.13 MANUFACTURING

The specific impact generated by the material manufacturing is the product of the manufactured mass and the impact factor corresponding to the fabrication process. The specific impact generated by the manufacturing of construction j is equal to the sum of each material contribution and is given by :

$$\overline{EI}_{j,l}^{Manufactue} = \sum_{i\in j}\left(\overline{EI}_{i,l}^{Manufactue}\right) = \sum_{i\in j}\left(\overline{M}_{i}^{Manufacture} \cdot IF_{i,l}^{Manufacture}\right) \tag{5.16}$$

where

j	Construction identification
i	Material identification in construction j
l	Impact identification
$\overline{M}_{i}^{Manufacture}$	Specific mass of material i manufactured, given by Eq. (5.15)
$IF_{i,l}^{Manufacture}$	Impact factor of impact l generated during the material manufacturing process in unit of impact per mass of material [Impact/kg]

According to the system boundary defined above, it should be kept in mind that the IF of the manufacturing process includes all the impacts generated from raw materials extraction up to the manufacturing of the construction material. It does not include the mass replaced during the building utilisation, which is accounted for in the replacement phase depicted in paragraph 5.19.

5.14 TRANSPORT FROM MANUFACTURING TO CONSTRUCTION SITE

After being manufactured, a material is transported to the assembly site, where it will be assembled with other materials. As each material has its own manufacturing site, the impact generated by the transport must take into account, for each material, the travelling distance and the means of transport used. The specific environmental impacts of construction j related to the transportation of the constituent materials i from the manufacturing site to the construction site are given by :

$$\overline{EI}_{j,l}^{Man\to Con} = \sum_{i\in j} ZF_i \cdot \sum_{m}\left(\frac{\overline{M}_{i,m}^{Man\to Cons}}{1000} \cdot TD_{i,m}^{Man\to Con} \cdot IF_{m,l}^{Transport}\right) \tag{5.17}$$

where

$\overline{M}_{i,m}^{Man\to Cons}$	Specific mass of material i manufactured, given by Eq. (5.14)
$TD_{i,m}^{Man\to Con}$	Distance covered with the means of transport m during the transport of material i from the manufacturing site to the construction site, in unit of distance [km]
$IF_{m,l}^{Transport}$	Impact factor for impact l due to the utilisation of the means of transport m, in unit of impact per distance and per mass of material [Impact/tonne/km]
ZF_i	Multiplication factor for material transport [-]

The ZF function expresses that the transport of a given mass requires a different number of journeys depending on the material density, because of the material volume. The lower the density, the higher the number of journeys that will be required. Figure 5.6 shows the shape of ZF and Appendix L gives more detail on how it has been obtained.

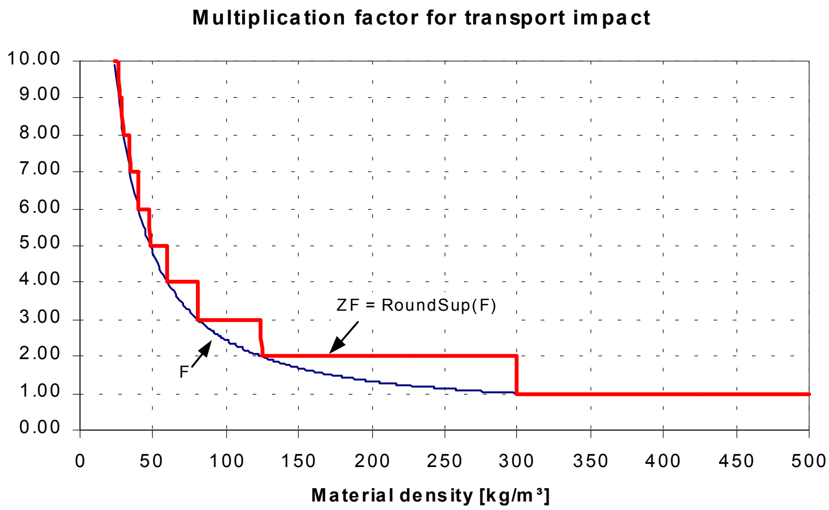


Figure 5.6 Multiplication factor ZF (ZF.xls)

In Eq. (5.17), it is assumed that the transportation process of a material can include several means of transport. For instance, glass might be transported first by train for a long distance journey and then from the railway station to the window assembly site by lorry. The environmental impact resulting from the transport process depends on the means used, the journey distance and the fraction of broken material.

5.15 CONSTRUCTION ASSEMBLY

At the construction site, the different materials are assembled one after the other until finally the construction is erected. The specific environmental impact generated during the construction assembly is the sum of the impact of the assembly of each material and is given by

$$\overline{EI}_{j,l}^{Assembling} = \sum_{i \in j} (IF_{i,l}^{Assembling}) \qquad (5.18)$$

where

$IF_{i,l}^{Assembling}$ Impact factor of impact l related to the assembling process of the material i in unit of impact per surface area [impact/m²].

This solution assumes that the material assembly is independent of the material mass. For instance, the assembly of insulation or plasterboard can be considered as independent of the material thickness. Although debatable, this first approximation is acceptable, as the *EI* related to the assembly phase may account for about 1% in the total impact generated by the building. Currently, there are only few data available for the assembly processes. Thus, the corresponding impact calculation proposed here may evolve in the future with the release of new data.

5.16 TRANSPORT FROM CONSTRUCTION SITE TO BUILDING SITE

After being assembled, a prefabricated element is transported from the construction assembly site to the building site where it will be placed on the building. All materials that constitute the prefabricated component are transported simultaneously with the same means of transport over the same distance during this phase. The specific environmental impact generated during the transportation of the prefabricated construction j from the construction site to the building site is given by:

$$\overline{EI}_{j,l}^{Con\rightarrow Buil} = \sum_{m} \left(TD_{j,m}^{Con\rightarrow Buil} \cdot IF_{m,l}^{Transport} \right) \cdot \sum_{i \in j} \frac{\overline{M}_{i,m}^{Cons\rightarrow Buil}}{1000} \cdot ZF_i \qquad (5.19)$$

where

j	Construction identification
m	Means of transport identification
l	Impact identification
$TD_{i,m}^{Con\rightarrow Buil}$	Transportation distance covered with the means of transport m during the transport of construction j from the construction site to the building site, in unit of distance [km]
$BL_{i,m}^{Con\rightarrow Buil}$	Fraction of broken and lost material i during the m^{th} transport from construction to the building site [-]
$IF_{m,l}^{Transport}$	Impact factor for impact l due to the utilisation of the means of transport m, in unit of impact per distance and per mass of material [Impact/tonne/km]
ZF_i	Multiplication factor for material transport [-]

Finally, it should be reminded that these environmental impacts exist only for building components that require a prefabrication phase. For materials that are directly transported from the manufacturing site to the construction site, this transport does not exist and then $TD_{i,m}^{Con\rightarrow Buil}$ is zero.

5.17 ASSEMBLY OF PRE-FABRICATED ELEMENT ON THE BUILDING

At the building site, a prefabricated element is added to the building. The impact l of the placement of the prefabricated element o n the building is then given by

$$\overline{EI}_{j,l}^{Add\ prefab} = IF_{j,l}^{Add\ prefab} \qquad (5.20)$$

where

$IF_{j,l}^{Add\ prefab}$	Impact factor of impact l generated when a prefabricated element is added to the building in unit of impact per surface area [impact/m²].

As for the construction assembly process, there are currently very few data available in the literature for this phase and therefore the same remarks are applicable.

5.18 CONSTRUCTION MAINTENANCE

During its life cycle, an element may be maintained periodically, for example to keep its physical properties (washing the window pane), to preserve its primary aesthetic aspect (painting a surface) or to ensure the occupants' health (using the vacuum cleaner). The environmental impacts related to the maintenance, which depend on the process and the frequency at which it is carried out, are given by :

$$\overline{EI}_{j,l}^{Maintenance} = \sum_u \left(BLS \cdot MF_u \cdot IF_{u,l}^{Maintenance} \right) \quad (5.21)$$

where

BLS	Building life span [y]
MF_u	Maintenance frequency of process u per year [y^{-1}]
$IF_{u,l}^{Maintenance}$	Impact factor l of maintenance process u [Impact/m^2]

The impact factor $IF_{u,l}^{Maintenance}$ is related to a single maintenance process, which occurs at the frequency MF_m each year. The number of times that the maintenance process takes place during the building life is then equal to $BLS\ MF_m$.

It may happen that published data merge the maintenance frequency and the impacts into a single value to express the impacts per year rather than per occurrence. If the maintenance period is known, it is possible to retrieve the impacts per process. In that case, the MF_m = 1/(process period) and the IF = (impacts published/MF_m). If the maintenance period is unknown, it is possible to store the impacts as published with a MF_m equal to the unity. For instance, in [KBOB1995], the energy of fitted carpet maintenance is equal to 4.1 [MJ/(m²y)], under the following conditions

- Weekly maintenance: Vacuum cleaner (1000W), 2x/week, 400 m²/h.
- Annual maintenance: Injection (high pressure) cleaning (1500W), 1x/year, 20 m²/h, 10g/m² of synthetic soap and 1100g/m² of water.

According to the previous considerations, the information can be stored in the two ways presented in Table 5.5.

Maintenance process of	Maintenance frequency [y^{-1}]	Impacts for the process [MJ/m²]	Comments
Fitted carpet	1	4.1	As published
	100	0.041	The impacts are expressed per maintenance process. It has been assumed that the maintenance process takes place twice a week except 2 weeks per year (end of year Holidays)

Table 5.5 Two possible solutions to storing the maintenance process.

The first solution is to store the data as published with a maintenance frequency of 1 [y^{-1}]. The second possibility consists in using the frequency of the maintenance of approximately 100 times per year, which corresponds to two maintenance processes weekly. Both solutions will predict the same environmental impacts when calculated over the building lifetime.
It should be noted that the environmental impact of a maintenance process may develop with time. As no one can accurately predict how the buildings and constructions might evolve through time, it is assumed that the maintained element and the maintenance process remain the same during the building life.

5.19 REPLACEMENT

The replacement takes place either at the end of the element's service life when it is too damaged to fulfil its initial function or earlier if it has been damaged in unexpected circumstances. The latter case is difficult to predict and therefore has not been taken into consideration here. Sophisticated approaches have been developed to assess the environmental impacts related to replacement. For instance, Burn [Bur1998] proposed a detailed model to estimate the material service life, which takes into account the degradation of building materials due to climatic and pollution aggression. But from the point of view of environmental impact calculation, the accuracy of the service life is less important than the adequate *IF* concerning the material manufacturing and elimination [Hàk1998].

The calculation method proposed here for the assessment of the impacts of the replacement phase assumes that the material service life, which is one of the data model attributes, depends only on the material and its functional use within the building. With this approach, different functional uses of a material may lead to different service lives. For instance, mineral wool insulation can be used for a double shell facade or for a pitched roof. Although made of the same basic material, the two mineral wool layers may have a different service life. The two materials may also have slightly different physical properties (density, conductivity, etc.) and thus it may be preferable to create two variant materials. The service lives used in this document are extracted from publications such as in [OCF1995; SIA1995a].

During the building life, a material may be replaced several times. The number of replacements Nr_i is a function of the material service life MSL_i and the building life span BLS. A first estimation of the number of replacements is given by $Nr_i = (BLT / MSL_i) - 1$. The term *-1* characterises the fact that the replacement phase includes only the materials used after the construction phase and does not include the materials used to erect the building. It should be stressed that Nr_i is a real number, but the effective number of times that a material is replaced in a real building corresponds to a round number (integer). It could be possible to only keep the integer part of the fraction result. For instance, if a building life span is assumed to be 80 years and a material has a life service of 37 years, then $Nr_i = 1.1$ and according to the previous assumption the material will be replaced once. And if the material service life is 27 years, then $Nr_i = 1.9$ and it will be replaced only once, as well. But in reality, it will certainly be replaced twice. To improve the Nr_i estimation it has been assumed that if the remainder of (BLS/MSL_i) -1 is ≥ 0.5, i.e. the remaining time is longer than the half time of the material, it will be replaced once more, otherwise it will not, which is expressed by

$$Nr_i = \begin{cases} \textbf{if } \left((BLS/MSL_i) - \mathrm{INT}(BLS/MSL_i)\right) < 0.5, \textbf{ then } \mathrm{INT}(BLS/MSL_i) - 1 \\ \textbf{if } \left((BLS/MSL_i) - \mathrm{INT}(BLS/MSL_i)\right) \geq 0.5, \textbf{ then } \mathrm{INT}(BLS/MSL_i) \end{cases} \tag{5.22}$$

where

INT	Integer part function, i.e. round the value to the first lower integer
Nr_i	Number of replacements of material *i*, in years [y]
BLS	Building life span, in years [y]
MSL_i	Service life of material *i*, in years [y]

This estimation of Nr_i assumes that the replacement of a material, wherever it is located within the construction, does not affect the other constituent materials, which is very unlike reality. For instance, the replacement of the internal insulation would probably result in the simultaneous replacement of the vapour barrier and the internal finish for financial or practical reasons.
Appendix M compares the result obtained with Eq. 5.22 with what may occur in reality for a building element, which leads to the conclusion that the difference between the two solutions is relatively small, especially when compared to the whole building LCA. Although it is a simplified description of the reality, the Nr_i obtained with Eq. (5.22) gives sufficiently satisfactory results and therefore has been retained.

Once the number of material replacements that occur during the building life has been determined, the impacts related to the replacement phase can be calculated. The replacements should take into account all the up-stream phases, including the material fabrication, its transport and finally its assembly within the construction, which is given by

$$\begin{aligned}\overline{EI}_{j,l}^{Replacement} &= \sum_{i\in j}\left(Nr_i \cdot \left(\overline{EI}_{i,l}^{Manufacture} + \overline{EI}_{i,l}^{Man\to Con} + \overline{EI}_{i,l}^{Assembling} + \overline{EI}_{j,l}^{Con\to Buil}\right)\right) \\ &\quad + \overline{Nr_j} \cdot \overline{EI}_{j,l}^{Add\ prefab}\end{aligned} \tag{5.23}$$

where

$$\overline{Nr_j} = \mathbf{INT}\left(\sum_{i=1}^{n}\frac{Nr_i}{n}\right) \tag{5.24}$$

Integer part of the mean service life of the constituent materials, in year [-]

$\overline{Nr_j}$ is used to average the effect of prefabricated element that is constituted of materials with different service life. Nevertheless, if the database is consistent, all the materials of a prefabricated element should have the same service life. For instance, for a window, the service life of the spacer and the frame would be equal to the service life of glass pane. In that case $\overline{Nr_j} = Nr_i$ and leads to the replacement of all the materials simultaneously.

5.20 BUILDING DECOMMISSIONING

At the end of the building life span, the building is dismantled. During that phase, the building materials are dissociated from the building. It is not rare nowadays to perform a selective deconstruction of the building, during which each material is separated on the building site. This process generates an impact given by:

$$\overline{EI}_{j,l}^{Decomissioning} = \sum_{i \in j} \left(IF_{i,l}^{Decomissioning} \right) \tag{5.25}$$

where

$IF_{i,l}^{Decomissioning}$	Impact factor for impact l generated during the decommissioning of material i, in units of impacts per surface area [Impact/m²]

Currently, decommissioning data are rare and the assessment of the decommissioning contribution may be improved in parallel to data release. Nevertheless, if the data are not available for a selective decommissioning, it may be acceptable in a first approximation to suppose that the decommissioning *IF* are equal to the assembly *IF*.

After being dissociated from the building, the construction might be dismantled and the constituent materials sorted by type according to the waste processing. As the waste screening is mainly done manually, this flow has been neglected here.

5.21 TRANSPORT TO THE WASTE MANAGEMENT SITE

After being sorted by material category, the waste materials are transported to the appropriate waste management site. Most of the materials require only one means of transport between the building site and the disposal site. This is generally the case for materials that are incinerated or put into storage in a landfill. Nevertheless, it may occur that materials require more than one means of transport. This might be the case for recovered materials, which are taken to a particular location using a given means of transport before they are sent further with yet another means of transport, to another site, where they will be recovered. It has been assumed that the means of transport and the covered distance depend on the waste type and therefore are material-related.

It is important to note that *all* materials mass used in a building must be transported to the waste processing site. This includes the materials necessary within the construction, the material lost during the assembly and the transport processes, and the material necessary for replacement. Thus, the mass of material i transported to the waste management site is equal to the mass of material manufactured during the building life span, which is given by

$$\overline{M}_i^{Waste} = \overline{M}_i^{Manufacture} \cdot \left(Nr_i + 1 \right) \tag{5.26}$$

Depending on the processing type, the material waste can be recovered (*Rec*), incinerated (*Inc*) and sent to a landfill (*Land*). For each waste management process, the mass sent to the appropriate site is given in by

$$\overline{M}_i^{Rec/Inc/Land} = \overline{M}_i^{Waste} \cdot MF_i^{Rec/Inc/Land} \tag{5.27}$$

where

$\overline{M}_i^{Rec/Inc/Land}$	Mass of material i recovered, incinerated or put in landfill [-].
$MF_i^{Rec/Inc/Land}$	Mass fraction of material i recovered, incinerated or put in landfill [-]. The sum of the three mass fractions must be equal to unity.

The $^{Rec/Inc/Land}$ is used to abbreviate the notation, which means that the equation is a triple equation applicable for each waste management process separately. Using the same notation, the environmental impact generated by the transport of the waste mass to the management site is given by:

$$\overline{EI}_{j,l}^{Building \rightarrow Rec/Inc/Land} = \sum_{i \in j} \frac{\overline{M}_i^{Rec/Inc/Land}}{1000} \cdot \sum_m \left(TD_{i,m}^{Building \rightarrow Rec/Inc/Land} \cdot IF_{m,l}^{Transport} \right) \tag{5.28}$$

where

i	Material identification in construction
j	Construction identification
m	Mean of transport identification
l	Impact identification
$TD_{i,m}^{Building \rightarrow Rec/Inc/Land}$	Distance covered with the means of transport m during the transport process of material i from the building site to the recovering, incineration or landfill site, in unit of distance [km].
$IF_{m,l}^{Transport}$	Impact factor for impact l due to the means of transport m used and expressed in units of impact per mass of material and per distance [Impact/tonne/km]

Here the multiplication factor ZF_i has been omitted. It has been assumed that waste materials are more or less compacted before their transport and therefore, the waste density exceeds 300 kg/m³, which leads to a $ZF_i = 1$ (see Figure 5.6).

It may be noted, that unlike the other transportation phases, no fraction of broken and lost material has been considered here. Furthermore, if one of the waste management channels is not relevant for a particular material, its corresponding MF_i should be equal to zero and thus no contribution to the transport process will be included.

5.22 WASTE MANAGEMENT

At the management site, the waste is processed according to the type of material. For a particular management channel, the processed mass corresponds to the mass fraction of the total mass of waste generated by the building during its life span. The environmental impacts for each of the three possible channels of waste management, i.e. recovering (*Rec*), incineration (*Inc*) and storage in landfill (*Land*) is given by:

$$\overline{EI}_{j,l}^{Rec/Inc/Land\ management} = \sum_{i \in j} \overline{M}_i^{Rec/Inc/Land} \cdot IF_{i,l}^{Waste\ management} \qquad (5.29)$$

where

i	Material identification in construction
j	Construction identification
l	Impact identification
$\overline{M}_i^{Rec/Inc/Land}$	Mass fraction of material i recovered, incinerated or put in landfill [-]. The sum of the three mass fractions should be equal to the unity.
$IF_{i,l}^{Waste\ management}$	Impact factor l for the waste management of material i, express in units of impact per mass of material [Impact/kg]

More sophisticated methods are available for the recovered fraction of material such as the closed and open loop, which permits accounting more precisely the corresponding impacts [Gau1997] and may be used later. The solution used in Eq. (5.29) is the classical assessment of the environmental impact generated by waste. With this approach the influence of using recycled materials for the building construction can be accounted for by using manufacturing impact factors adapted to the quality of the construction materials used. For instance, Table 5.6 shows the impact factors of the manufacturing of two different qualities of aluminium. As can be seen, recycled aluminium generates approximately ten times lower impacts than new aluminium. The use of different qualities will affect the LCIA of the manufacturing phase for which the use of a recycled material will have a lower impact. But the downstream phases, such as the transport and assembly, will not be affected.

Material	Impact factor			
	NRE [MJ/MJ]	GWP [kg CO2-eq./MJ]	AP [g SOx-eq./MJ]	POCP [g NOx-eq./MJ]
Aluminium 0% recycled	175.00	10.60	73.90	19.70
Aluminium 100% recycled	18.20	1.10	4.49	1.47

Table 5.6 Impact factors for two different quality of aluminium (Source [Sut1996]).

This paragraph ends the section dedicated to the presentation of the calculation proposed for assessing the specific environmental impact for each life cycle phase. The remainder of this chapter is focused on the interface of the LCIA module implemented in ESP-r.

5.23 LCIA INTERFACE

A complete LCIA requires the calculation of the extrinsic and intrinsic contribution. The original capabilities of ESP-r enable the assessment of the annual energy consumption, which is used to calculate the extrinsic impacts, but for the intrinsic contribution, a new module had to be implemented. The interface of the LCIA module, which copies the interface structure of the other ESP-r modules, consists of a graphical and textual feedback, and a contextual menu as shown in Figure 5.7.

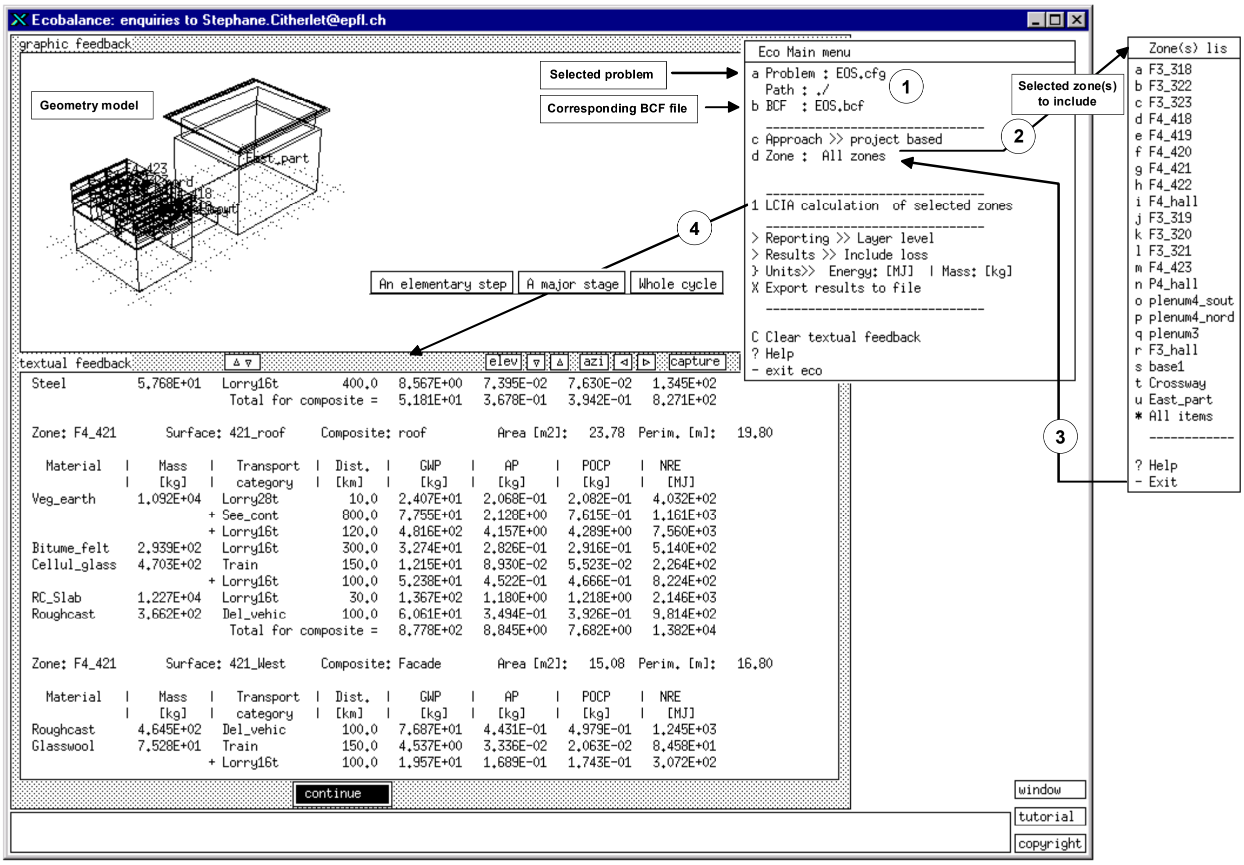


Figure 5.7 LCIA interface implemented in ESP-r.

At the start of the LCIA module, the project is loaded and the corresponding geometry model is displayed in the graphical feedback (see ① in Figure 5.7). Then the BCF file, which holds the physical attributes of the constructions used within the project, is loaded.

The standard procedure to perform a LCIA consists of selecting:

- The part of the project to analyse. It can either be the whole project, selected zones or selected constructions (see ② in Figure 5.7).

- The life cycle phase(s) to include. The offered possibilities are : (a) an elementary phase, (b) a major phase (construction, utilisation or deconstruction) or (c) for the whole building life span (see ③ in Figure 5.7). When selected, the module performs the LCIA calculation and displays the results (see ④ in Figure 5.7).

Before running the calculation, the reporting options listed in Table 5.7 can be modified. For instance, the reporting level can be adapted to the analysed object. The most compact output format returns a single set of impacts, each of which sums all the contributions generated by each life-cycle phase of each material, for each surface within the project. For a more detailed analysis, the impacts can be detailed up to the material level, for each life cycle phase of each material within the project. This verbose output format is suitable for the LCA of a material or a construction and shows in detail the environmental impacts of each material within the project.

Options	Effects
> Reporting >> Layer level	Selection of the reporting level. The results can be displayed either by material, zone surfaces or by zone.
* Results >> Include loss	Define whether or not the material loss (during transport and assembly phase) must be included for the LCIA. Although it should always be included in the LCIA calculation, excluding the loss permits appraising its influence on the results.
} Units>> Energy: [MJ] | Mass: [kg]	Selection of the result units: For energy (NRE) the unit can be switched between [MJ] and [kWh]. And between [kg] and [g] for mass (GWP, POCP and AP).
X Export results to file	Defines the file to which the results can be exported

Table 5.7 Reporting options in the LCIA module.

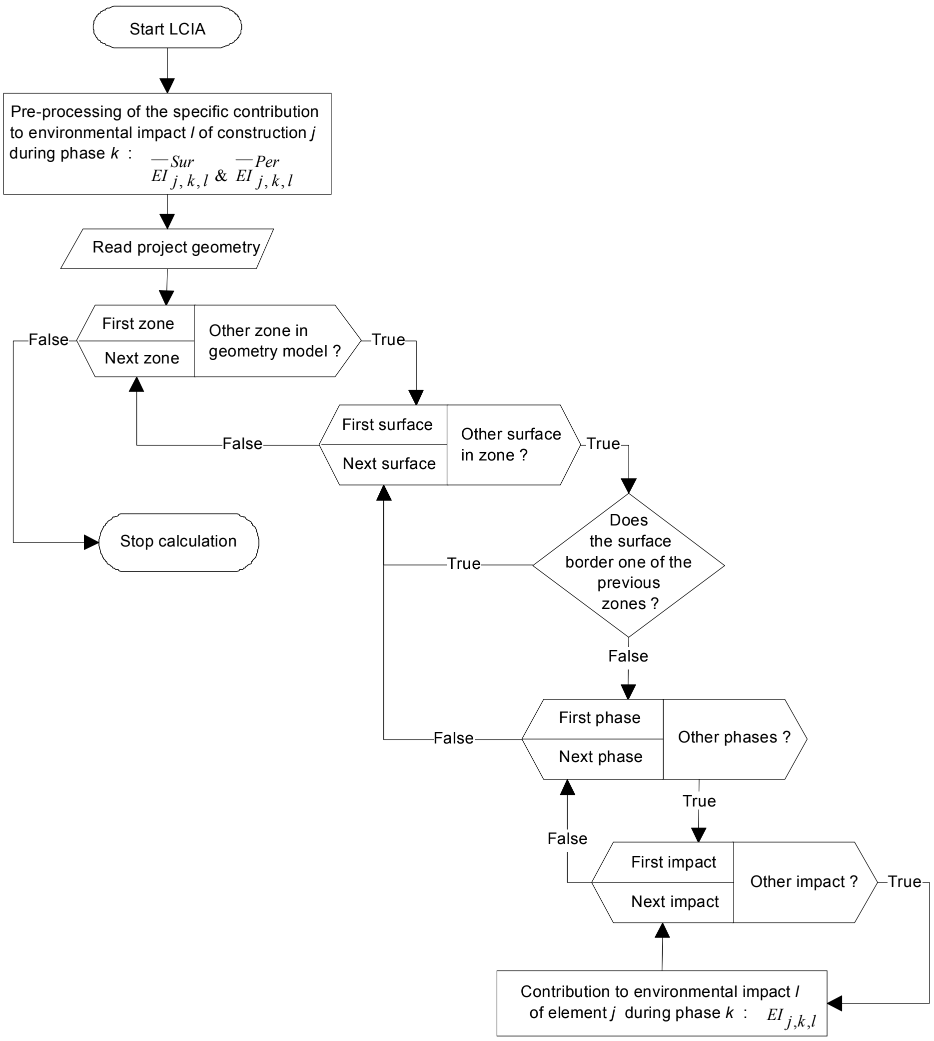


Figure 5.8 Environmental impact calculation of a project. (EI calculation (petit).flo

The LCIA assessment starts by the pre-processing of the specific environmental impact ${}^{Sur}\overline{EI}^{k}_{j,l}$ and ${}^{Per}\overline{EI}^{k}_{j,l}$, for each construction itemised in the project. Then the geometry is scanned zone after zone as shown in Figure 5.8. During this process, the zones are scanned to locate all the existing boundary surfaces. When a surface is found, a first analysis determines if it had already been detected in a previous zone. This is necessary to avoid double accounting the impacts of a surface that borders two zones. If a surface has already been taken into account, it is skipped and the scanning continues. Otherwise, the ${}^{Sur}\overline{EI}^{k}_{j,l}$ and ${}^{Per}\overline{EI}^{k}_{j,l}$ of the corresponding construction are retrieved from the pre-processing step. The environmental impact of the surface is calculated and the result is added to the intrinsic impact of the building. This looping process takes into account all the elements defined in a geometry model and is iterated until the last surface of the last zone is detected.

5.24 FUNCTIONAL UNIT

The comparability of the results is critical for the evaluation of environmental impacts of different systems and requires the normalisation of the results. In the LCIA the functional unit (FU) of the system is used to describe the main function of a product and indicates how much of this function is considered. It enables an objective comparison of different solutions normalised to the same unit. For instance, a popular adage says that it is not possible to add an apple and a pear. This is true as long as no FU is defined. If the FU is, for instance, the volume, the weight or the calorific content of the product, then the two kinds of fruit can be added without ambiguity.

The selection of the FU can have a major effect on the LCIA results. For instance, Jolliet [Jol1999] shows that popcorn used as a filling material in packaging generates a lower environmental impact during the manufacturing phase than polystyrene chips. In this case, the FU is expressed in mass of filling material. However, the popcorn density is more than four times the density of the polystyrene chips and thus a given volume filled with the natural material is heavier than the same volume filled with the synthetic product. This supplementary mass (for the same volume) has a major influence on the environmental assessment of the transportation phase. Thus, if the FU is the environmental impact per unit of volume transported over a certain distance, the tendency is reversed due to the influence of the transportation impact. This example illustrates that the FU has to be defined in order to pragmatically analyse the results. As a corollary, the system boundaries need to be defined in any LCIA and the same boundaries must be used when comparing variants.

When comparing two variants of a building, a logical approach would be to compare the environmental impact of variants that provide the same occupant comfort. This is possible as long as the comfort can be guaranteed to be equivalent in both variants, which is conceivable with mechanical equipment that could compensate the building reaction to the external climate. In a building without adequate equipment, a constant occupant comfort cannot be guaranteed. Two variants of a building, with different internal surfaces, will lead to different occupant comfort (thermal, acoustic, etc.). Thus, comfort criteria cannot be used systematically and other FUs have to be defined. A more pragmatic solution is to calculate the environmental impacts of the building expressed either in absolute value, per net gross floor area over the building life span or per net gross floor area and per year. Table 5.8 lists the possible FU's considering the part of the building analysed.

LCA of	FU
Whole project	Absolute, m² of floor area, m² of floor area/year
Zone	Absolute, m² of floor area, m² of floor area/year
Construction	Absolute, kg or m² of construction, kg or m² of construction/year
Material	Absolute, kg or m² of material, kg or m² of construction/year

Table 5.8 Possible functional unit (FU) depending on the analysed product.

It is possible to compare two construction variants that play the same role (independently of any project) and to express the FU as the impacts generated per surface area as for instance in [SIA1995a], which allows a comparison of building elements according to their function in the building.

In summary, this chapter has presented a detailed method for the assessment of the environmental impacts generated by a building during its whole life span, which fulfils the requirements of the ISO 10303 standard for the life cycle impact assessment (LCIA).

The LCIA described here includes two distinct contributions: (1) the extrinsic contribution generated by the energy consumed to provide services during building operation, which is calculated on the basis of the annual energy consumption simulated by ESP-r, and (2) the intrinsic impact generated by the mass and energy flows required by the elements of a building through the whole building life span. To cover any possible contribution, it includes the material manufacturing, transport and assembly processes, the mass of material lost during these processes, the maintenance and replacement generated during building utilisation as well as the waste transport and management resulting from the building decommissioning.

The LCIA methodology proposed in this work is independent of the impact assessment methodology used to provide the environmental data, but one inventoried load (NRE) and three environmental effects (GWP, AP, and POCP) extracted from the CML method are used as environmental indicators.

To support the assessment of the intrinsic contribution, a new module has been implemented in ESP-r. The module scans the geometry model surface by surface and performs the LCIA with the help of the building construction file (BCF), which stores the constructions description.

CHAPTER 6

ROOM ACOUSTICS

Building acoustics was implemented as an additional view in ESP-r to demonstrate the feasibility of the proposed approach. Among the different domains of building acoustics, room acoustics was selected for several reasons. First, it has a major impact on the quality of the indoor environment, which influences the occupant comfort. Second, a space with acceptable room acoustics requires solutions that generally reduce the thermal inertia of the building. The assessment of this inter-dependent behaviour is particularly important in modern architecture. As can be seen in Figure 6.1, for a particular frequency, an agglomerated fibreboard panel with mineral wool fixed on a rigid support (reinforced concrete) does not absorb the same fraction of sound as the same composition without the mineral wool. If the reinforced concrete is covered with roughcast finish (bottom wall typology in Figure 6.1), it is a poor sound absorber, but has a good thermal inertia, which increases absorption of the solar gains and may improve the thermal comfort. On the other hand, if the concrete is covered with an acoustic absorbent material, such as agglomerated fibreboard (top wall typologies in Figure 6.1), the sound absorption increases but the thermal inertia is reduced. In consequence, the material composition of a construction influences its acoustic absorption properties and also affects the thermal inertia of the construction. It is important to find a balance between sound absorption and thermal inertia to provide an acceptable thermal comfort and room acoustics performance.

Room acoustics addresses the perception of the sound quality within a space, which can be characterised by several indicators. In this work the *reverberation time* is used, as it is a well-known metric quality. The reverberation time calculations implemented here correspond to three versions of the diffuse-field theory. They take into account sound absorption due to the room boundaries, the furniture and the occupants, and the enclosed air. To improve the room acoustics assessment, the air absorption is calculated as a function of the air temperature and humidity, which are appraised with the thermal simulation.

The reverberation time is appraised with three different formulations of the diffuse-sound field theory: the Sabine, Eyring and Millington equations. The absorption includes the enclosure boundaries, the possible occupants and furniture, and the enclosed air. Other simulation methodologies, such as the image-source or ray-tracing approach, could also be used to assess the reverberation time. The computer model in ESP-r would have allowed the implementation of these different approaches, but would have been too time consuming with respect to the goals of the present work.

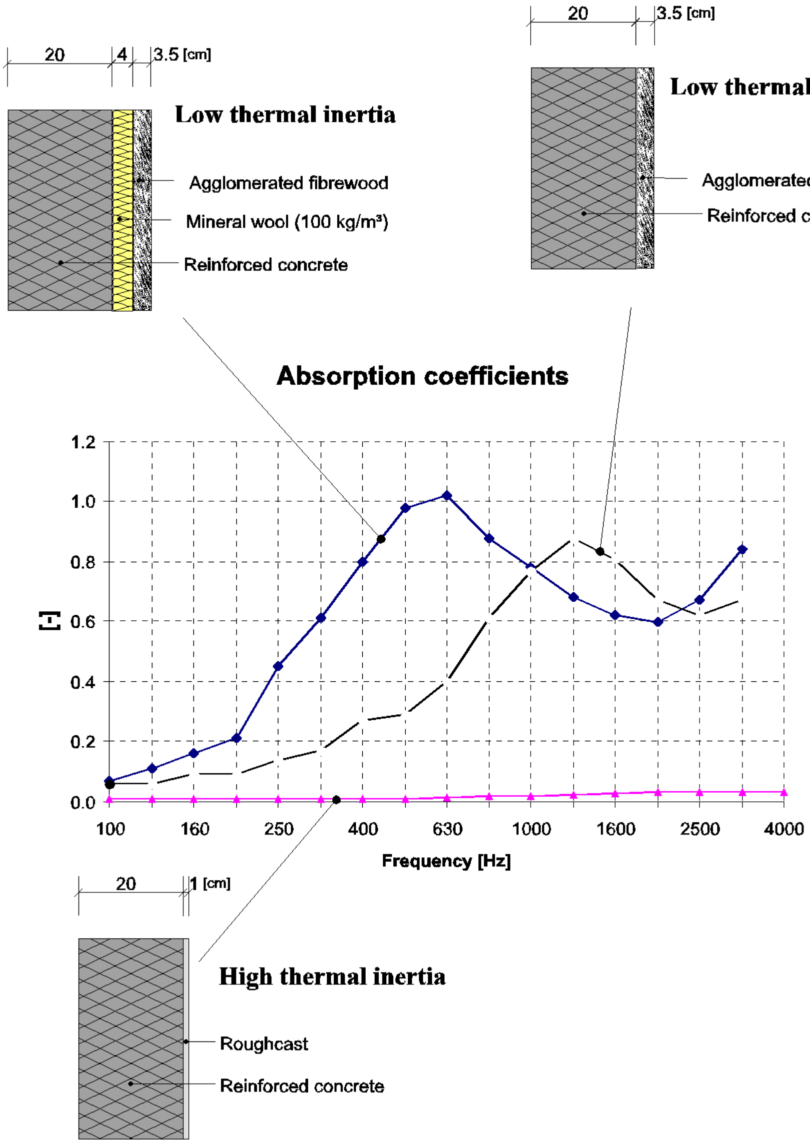


Figure 6.1 Acoustic absorption coefficients of three wall typologies (right hand side surface). (Effusivity vs Acoustic-small.dsf)

6.1 REVERBERATION WITHIN AN ENCLOSURE

After a source starts emitting sound, all parts of the enclosure are filled with reflected sound travelling in many different directions. These reflected waves increase the sound pressure level within the space, producing a persistent and steady state sound as long as the source is emitting.
If the source is stopped, the sound decreases during a certain time due to the multiple reflections of sound at the enclosure boundaries. At each successive reflection, the enclosure boundaries and the objects within it absorb a fraction of the sound energy. The remaining energy fraction is reflected within the space, so that the sound takes a certain time to vanish. This remanence of sound is referred to as the reverberation of the room.
The decay rate of the sound depends on the boundary materials, the air volume and the sound frequency spectrum. The fraction of absorbed sound energy depends on the frequency of the emitted sound and the capacity of a material to absorb this frequency.

To summarise, the greater the room volume and/or the less absorbent surfaces it contains, the longer will be the duration of the reverberation. A limited amount of reverberation is however desirable but excessive reverberation may lead to the overlapping of syllables and/or musical notes, which has a deleterious effect on intelligibility.

6.2 REVERBERATION TIME

For a given frequency *f*, the reverberation time T_f^{rev} is the time the average sound pressure takes in a space, after the source has stopped, to decrease by a factor of one thousand: this corresponds to a sound pressure level difference of 60 dB. The calculation methods used in this work to assess the reverberation time are based on different versions of the diffuse-field theory: the Sabine, the Eyring and Millington equations. The basic assumption of the diffuse-field theory is that the sound field in the room is diffuse, which occurs if "*at any position in the room, the reverberate sound waves are incident from all directions with equal intensity and with random phase relations*" [Ber1988].

The three versions of the reverberation time equations can be expressed by the following synthetic expression:

$$T_f^{rev} = \frac{55.3}{c} \cdot \frac{V}{A_f^{Tot}} \tag{6.1}$$

where

V	volume of the enclosure [m³]
f	frequency under consideration [Hz]
A_f^{Tot}	total equivalent area of the enclosure for frequency *f* [m²]
c	sound speed in air [m/s]

The total equivalent area A_f^{Tot} of the enclosure represents the area of a perfect absorber that would have the same absorption impact as the actual absorption of the surface materials within the enclosure.

In accordance with the standard ISO 266 [ISO1975a], the frequency band used to assess the reverberation time is either the one octave band (centre frequencies 125, 250, 500, 1000, 2000 and 4000 [Hz]) or the one-third octave band (centre frequencies 100, 125, 160, 200, 250, 315, 400, 500, 630, 800, 1000, 1250, 1600, 2000, 2500, 3150 and 4000 [Hz]).

In Eq. (6.1), the total equivalent area A_f^{Tot} of the enclosure includes the absorption due to the boundaries, the furniture and the occupants, and the air, which can be written:

$$A_f^{Tot} = A_f^{Bound} + A_f^{Obj-Pers} + A_f^{Air} \tag{6.2}$$

where

A_f^{Bound}	equivalent absorption area of the enclosure boundaries [m²]
$A_f^{Obj-Pers}$	equivalent absorption area of the objects in the enclosure [m²]
A_f^{Air}	equivalent absorption due the enclosed air [m^2]

The enclosure boundaries are either an enclosure surface, such as the floor or the ceiling or a piece of furniture that has been placed in front of one of the enclosure boundaries, such as a cupboard. If it is a piece of furniture, the part of the surface hidden by the furniture should not be taken into account in the calculation of A_f^{Bound}, as it is not involved in the absorption mechanism.

6.3 ABSORPTION OF BOUNDARIES

Different expressions have been proposed to assess the equivalent absorption area of the enclosure boundaries A_f^{Bound}. To demonstrate the feasibility of the integrated approach proposed in this work, three of the most used analytical expressions are presented below, which were implemented in ESP-r to assess the reverberation time.

6.3.1 Sabine equation

In the first expression proposed by Sabine [Sab1993] to assess the reverberation time, the total equivalent absorption area of the enclosure boundaries is given by:

$$A_f^{Bound} = S \cdot \overline{\alpha}_f^{Sab} = \sum_i^{bound} \left(S_i \cdot \alpha_{i,f}^{Sab} \right) \tag{6.3}$$

with

$S \equiv \sum_i S_i$ total surface area of the enclosure [m²]

$$\overline{\alpha}_f^{Sab} \equiv \frac{\sum_i^{bound} \left(S_i \cdot \alpha_{i,f}^{Sab} \right)}{S}$$ average absorption coefficient at frequency *f* [-] (6.4)

and where

S$_i$	area of surface *i* [m²]
$\alpha_{i,f}^{Sab}$	Sabine absorption coefficient of surface *i* at frequency *f* [-]

The meaning of the Sabine equation is that each time a wave strikes one of the enclosure boundaries, on average a fraction $\overline{\alpha}_f^{Sab}$ of the energy is absorbed and a fraction (1-$\overline{\alpha}_f^{Sab}$) is reflected. Although it appears to be simple, a first limitation of the Sabine equation was obtained when reverberation time measurements showed that α_i^{Sab} could exceed 1 for very absorbent material if equations (6.1) and (6.4) were applied. This means that the material absorbs more energy than the incident energy, which is not possible. The Sabine equation is inappropriate for predicting the reverberation time for enclosures with high absorbing materials, as shown with the following reasoning. When the surfaces in an enclosure work as a perfect sound absorber, i.e. $\alpha_{i,f}^{Sab} \to 1$, no sound is reflected and therefore, the reverberation time $T_f^{rev} \to 0$.
Unfortunately, if the hypothesis of high absorbing materials is applied to the Sabine equation, the reverberation time of an empty enclosure leads to the following expression

$$\lim_{\alpha_{i,f}^{Sab} \to 1} T_f^{rev} \approx \frac{55.3}{c} \cdot \frac{V}{S + A_f^{Obj-Pers} + A_f^{Air}}$$

The reverberation time becomes then a function of the shape of the enclosure, i.e. tends to become zero only when $S >> V$, which is in contradiction with the previous statement. Sabine's formula is therefore accurate only if $\overline{\alpha}_f^{Sab} << 1$, i.e. for reverberating enclosures. For instance, Jouhaneau [Jou1997] proposes to use the Sabine equation only when $\overline{\alpha}^{Sab} < 0.2$. To overcome the difficulty encountered with the Sabine equation when applied to highly absorbent materials, statistical approaches to the sound absorption mechanisms have been proposed. In the Sabine approach, the sound decay is assumed to be a continuous process. The statistical approach assumes that sound wave energy is absorbed at each reflection and uses the statistical absorption coefficient $\alpha_{i,f}^{E}$ which represents the ratio of sound energy absorbed at frequency f by a surface of infinite extent to the sound energy incident upon the surface when the sound field is perfectly diffuse [Mor1987] instead of the $\alpha_{i,f}^{Sab}$.

Based on the statistical approach, several techniques have been used to derive the total equivalent absorption area of the enclosure boundaries. In ESP-r, the following two methods have been implemented.

6.3.2 Millington equation

The first approach consists of following a sound ray and determining its energy decay after several reflections. Based on this method, Millington [Mil1932] ends up with the equivalent absorption area of the boundaries given by:

$$A_f^{Bound} = \sum_i^{bound} \left(S_i \cdot \ln\left(\frac{1}{1-\alpha_{i,f}^{E}}\right) \right) \tag{6.5}$$

where

- S_i area of surface i [m²]
- $\alpha_{i,f}^{E}$ statistical (energy) absorption coefficient [-]

The Millington formulation of the total equivalent absorption area A_f^{Bound} is compatible with the reverberation time observed within in an enclosure of highly absorbing materials. In that case, the Millington equation leads to $T_f^{rev} \to 0$, independently of the room shape, which correspond to the reality in contrast to the Sabine equation.

Nevertheless, the Millington equation encounters difficulty if a surface, no matter how small, has a sound absorption coefficient approaching unity and the remaining surfaces have sound absorption coefficients approaching zero. According to Eq. (6.2), such a case leads to a $A_f^{Bound} \to \infty$ and thus Millington will predict a reverberation time that tends towards zero, which is not realistic. Therefore, the equation can be used independently of the absorption (high or low) of the surfaces, but these must have similar absorption coefficients: the Millington equation should not be used when the absorption values of the materials are very different. For instance, in a room with a fitted carpet with a ceiling and walls made of roughcast on concrete, the results obtained with the Millington equation might not correspond to reality.

6.3.3 Eyring equation

The second method based on the statistical approach, due to Eyring [Eyr1930], considered a beam of parallel rays that strike several different surfaces S_i. In that case, the absorbed energy is the sum of the energy absorbed by each individual surface. This leads to the Eyring formulation of the total equivalent absorption area given by

$$A_f^{Bound} = -S \cdot \ln(1-\overline{\alpha}_f^E) = -S \cdot \ln\left\{1 - \frac{1}{S}\sum_i^{bound} S_i \cdot \alpha_{i,f}^E\right\} \qquad (6.6)$$

where

S_i area of surface i [m²]

$\alpha_{i,f}^E$ statistical (energy) absorption coefficient [-]

For a very absorbing enclosure, i.e. $\alpha_{i,f}^E \to 1$, Eq. (6.6) leads to

$$\ln\left\{1 - \frac{1}{S}\sum_i^{bound} S_i \cdot \alpha_{i,f}^E\right\} \to -\infty \qquad \text{and} \qquad A_f^{Bound} \to \infty$$

In that case, the Eyring equation leads to a reverberation time $T_f^{rev} \to 0$. And whereas the Millington equation is in error when one surface, however small, has a $\alpha_{i,f}^E$ approaching unity (in which case $T_f^{rev} \to 0$), the Eyring equation predicts a finite T_f^{rev} because the contribution of each surface is weighted with all the surfaces in the enclosure.

For specular reflecting surfaces, the Eyring prediction is accurate in a regularly shaped enclosure with uniform absorption. But the Eyring equation is applicable for any average surface-absorption coefficient as long as the surface absorption is uniformly distributed [Hod1996].

6.4 ABSORPTION COEFFICIENTS

It should be noted that the statistical (energy) absorption coefficient $\alpha_{i,f}^{E}$ is, strictly speaking, not equal to the Sabine absorption coefficient $\alpha_{i,f}^{Sab}$. The latter is defined for a surface of finite extent, while $\alpha_{i,f}^{E}$ requires a surface of infinite extent, which is not possible in practice. The difference between $\alpha_{i,f}^{Sab}$ and $\alpha_{i,f}^{E}$ is caused by the diffraction of the sound field, especially at low frequencies, when incident on a sample of finite size [Ber1988]. Most of the published sound absorption coefficients are $\alpha_{i,f}^{Sab}$, as they result from measurements of a finite size sample in a standardised reverberation room. The characteristics of the room, which are defined by the ISO [ISO1985], must ensure a diffuse reverberating sound field. The sound absorption coefficients $\alpha_{i,f}^{Sab}$ can be calculated with the help of the Sabine equation by measuring the reverberation time in the standardised room with the considered material and comparing the results with those obtained in the empty room. Therefore, in practice the $\alpha_{i,f}^{Sab}$ is used in Eyring and Millington equations.

Table 6.1 summarises the conditions of validity of the Sabine, Millington and Eyring equations and the expressions of the equivalent absorption area of the enclosure boundaries A_f^{Bound} to be used in Eq. (6.1).

	Sabine	Millington	Eyring
Absorption coefficients	$\overline{\alpha}^{Sab} < 0.2$	$\overline{\alpha}^{Sab} \geq 0.2$ and $\alpha_{i,f}^{Sab}$ do not $\rightarrow 1$	$\overline{\alpha}^{Sab} \geq 0.2$
Equivalent area of the boundaries A_f^{Bound}	$\sum_i^{bound} \left(S_i \cdot \alpha_{i,f}^{Sab}\right)$	$\sum_i^{bound} \left(S_i \cdot \ln\left(\frac{1}{1-\alpha_{i,f}^{Sab}}\right) \right)$	$-S \cdot \ln\left\{1 - \sum_i^{bound} \frac{S_i \cdot \alpha_{i,f}^{Sab}}{S}\right\}$

Table 6.1 Selection criterions of the reverberation model.

Whatever the equation used, it should be remembered that if the theoretical assumptions do not hold in the case of a particular enclosure for which the predictions are to be made, the results may not be accurate. The theoretical model from which the Sabine, Millington and Eyring equations are derived requires that the decaying sound field be perfectly diffuse. This highly idealised condition is sufficiently fulfilled in practice when: (a) no room dimension is markedly different from the others; (b) room dimensions are large compared to the wavelength, which is the case in building acoustics; (c) absorption is distributed almost uniformly over the enclosure boundaries.
To overcome these limitations, several other refined approaches based on the diffuse-field theory have been developed to evaluate T^{rev}, such as the one defined by Fitzroy [Fit1959], one by Arau-Puchades [Ara1988] or one based on a time series approach [Ska1994]. In addition, the new version of the CEN standard dedicated to the calculation of the reverberation time [CEN2000], which is in consultation at the moment of the printing of this document, is a refined version of the Sabine equation.

As mentioned in the beginning of this chapter, the calculation methods retained in this work have been selected to demonstrate the feasibility of the integrated approach within the time assigned to this work. They are a compromise between result accuracy and the effort necessary to implement the methods in ESP-r. Nevertheless, the physical data model implemented in ESP-r does not limit the calculation methods to analytical solutions, but also supports simulation methods such as image source [Lee1988], ray-tracing [Kul1984], cone/pyramid tracing [Fai1995] and hybrid approach [Lew1993; Vor1989].

6.5 EQUIVALENT AREA OF OBJECTS AND OCCUPANTS

The Eq. (6.1) requires the equivalent absorption area of the objects and persons in the enclosure $A_f^{Obj-Pers}$, which is given by:

$$A_f^{Obj-Pers} = \sum_j^{objects} \left(N_j \cdot A_{j,f}^{Obj}\right) + \sum_k^{persons} \left(P_k \cdot A_{k,f}^{Pers}\right) \tag{6.7}$$

where

$A_{j,f}^{Obj}$ equivalent absorption area of object j at frequency f [m²]

N_j number of occurrences of object type j

$A_{k,f}^{Pers}$ equivalent absorption area of person k at frequency f [m²]

P_k number of occurrences of person type k

The equivalent absorption area of common objects and persons can be found in the specialised literature. For rigid and irregularly shaped objects (desk, computer, etc.), the equivalent area can be important but might not be available in the literature. In that case, the following approximation, proposed in [CEN2000], can be used to estimate the equivalent absorption area of a rigid object, such as a desk:

$$A_{j,f}^{Obj} = \left(V_j^{Obj}\right)^{2/3} \tag{6.8}$$

where

V^{Obj} volume of the rigid object j

It should be noted that not all objects in the enclosure need to be taken into account. Rigid and small objects, such as a handle, will not have a significant influence on $A_{i,f}^{Obj}$, where all the contributions (boundaries, objects, persons and air) are summed, and therefore might be ignored.

6.6 AIR ABSORPTION

The thermodynamic properties of air affect the fraction of sound energy that is absorbed by the air. Air absorption is sensitive to air temperature, air composition, particularly water vapour concentration, and sound frequency. There are two basic mechanisms:

- *Classical losses* are associated with the transfer of acoustic energy (organised motion associated with the kinetic energy of the molecules) into equivalent heat energy (uncoordinated motion associated with thermal agitation).

- *Relaxation losses* are associated with the redistribution of internal energy that occurs during the collision of gas molecules.

In small enclosures, the number of reflections is large and the sound travel distance between reflections is comparatively small. The air absorption can therefore be neglected, especially in enclosures covered with relatively high absorbing materials. Thus the equivalent area of the components is large compared to the air absorption and it can be assumed that $A_f^{Tot} \cong A_f^{Bound} + A_f^{Obj-Pers}$ whatever the frequency. But for large enclosures, the distance travelled by the sound waves through the air is much larger and the energy loss in the air cannot be ignored at frequencies equal or above 1 [kHz].

In a medium-sized enclosure (300 [m³]) with low absorbent materials, the air absorption may represent 20 to 25 percent of the total absorption in a reverberating space [Eve1989]. In a larger space, at a frequency around 4 [kHz], the absorption due to air may be comparable to the absorption of the surface materials and therefore has to be taken into account independently of the surfaces absorption. For instance, in the Llewellyn Hall (12750 [m³]) in Canberra, an inland city with low humidity and cold nights, an extremely low relative humidity was obtained (around 25%) when outside air was used to ventilate the concert hall. For occupant comfort, the internal relative humidity had to be maintained at about 55%, which increased the reverberation time. For instance, at 4 [kHz], the reverberation time passes from 1.25 [s] to 1.70 [s] for a relative humidity of respectively 25% and 55% [McC1990]. To keep the acoustical quality independent of the climate condition, a mechanical ventilation system had to be installed. This example illustrates the influence of the thermo-physical properties of the air on the room acoustics, which may require integrated assessment.

To take account of these mechanisms, the calculation of the reverberation time must include the absorption associated with the air enclosed in the analysed space. The equivalent absorption due the enclosed air A_f^{Air} can be expressed (see for instance [Knu1978]) by:

$$A_f^{Air} = 4m \cdot V \tag{6.9}$$

where

m	air absorption coefficient [m^{-1}].
V	volume of the enclosure [m³]

Measurements undertaken by Harris [Har1966] have shown that m depends on the temperature and the relative humidity of the air in the enclosure, and the sound frequency f. For usual humidity and temperature values in buildings, m increases proportionally to the square of the frequency (f^2) and consequently becomes important at high frequencies. Table 6.2 shows the air absorption coefficient m as tabled per octave band for several air temperatures and relative humidity ranges extracted from [CEN2000].

Air condition	$4m$ [10^{-3} m^{-1}], for octave bands with centre frequency in [Hz]					
	125	250	500	1000	2000	4000
10 °C, 30-50% humidity	0.5	0.9	1.8	4.4	10.2	36.0
10 °C, 50-70% humidity	0.4	0.9	1.7	3.1	6.9	23.1
10 °C, 70-90% humidity	0.3	0.9	1.8	3.0	5.7	17.5
20 °C, 30-50% humidity	0.5	1.3	2.4	3.9	7.4	22.0
20 °C, 50-70% humidity	0.4	1.1	2.6	4.1	6.6	16.1
20 °C, 70-90% humidity	0.3	1.0	2.6	4.1	6.7	14.1

Table 6.2 Sound absorption coefficient m in octave bands, depending on temperature and relative humidity.

As can be seen in Table 6.2, if the relative humidity increases, m decreases and according to Eq. (6.6), the air absorption A_f^{Air} decreases, which finally leads to the increase of the reverberation time (see Eq. (6.1) and Eq. (6.2)).

To improve the T_f^{rev} assessment, m can be expressed for specific air conditions. In that case, a more detailed formulation must be used. For computer simulation, an expression of the sound absorption coefficient m can be derived from the sound attenuation coefficient α^{att} [dB/m] defined by the ISO 9613/1 [ISO1993] and by using the relation α^{att} = 4.34m [Lie1983], which leads to the following expression:

$$m = 3.68 \cdot 10^{-11} f^2 \left(\frac{p}{p_0}\right)^{-1} \left(\frac{T}{T_0}\right)^{1/2} + \left(\frac{T}{T_0}\right)^{-5/2} \left(0.1068 \cdot e^{\frac{-3352.0}{T}} \cdot \frac{2f^2}{f_{rN} + \left(\frac{f^2}{f_{rN}}\right)} + 0.0128 \cdot e^{\frac{-2239.1}{T}} \cdot \frac{2f^2}{f_{rO} + \left(\frac{f^2}{f_{rO}}\right)} \right) \tag{6.10}$$

where

f	frequency of the sound [Hz]
p	air pressure [kPa]
p_0	reference air pressure (101.325) [kPa]
T	absolute temperature of the air [°K]
T_0	reference air temperature (293.15) [°K]
f_{rN}	relaxation frequencies for Nitrogen [Hz]
f_{rO}	relaxation frequencies for Oxygen [Hz]

The Appendix N presents the detailed formulation of m presented in Eq. (6.9). It also includes the expression of the relaxation frequencies f_{rO} and f_{rN} as a function of the air temperature and humidity.

6.7 SOUND SPEED

The thermodynamic properties of air also influence the sound speed c used in Eq. (6.1). If it is assumed that air behaves as an ideal gas, which is reasonable for the temperature and densities under consideration, c is dependent only on the absolute temperature of the air. In that case, the speed of sound formulation in ISO 9613/1 [ISO1993] is given by :

$$c = 343.23 \cdot \sqrt{\frac{T}{T_0}} = 20.05 \cdot \sqrt{T} \qquad (6.11)$$

where

T	absolute temperature of the air in the enclosure [°K]
T_0	reference temperature of the air (293.15) [°K]

According to Eqs (6.1) and (6.12), the reverberation time can be written as:

$$T_f^{rev} = K_\theta \cdot \frac{V}{A_f^{Tot}} \qquad \text{with} \qquad K_\theta = \frac{2.76}{\sqrt{T}} \qquad (6.12)$$

where

V	volume of the enclosure [m³]
A_f^{Tot}	total equivalent area of the enclosure for frequency f [m²]

The Figure 6.2 represents the value of the term K_θ used as a function of room air temperature. At 20 °C, $K_\theta \cong 0.161$ [s/m], which is the constant value generally used as a first approximation in the literature, when the sound speed c is assumed to be constant and equal to 343.3 [m/s].

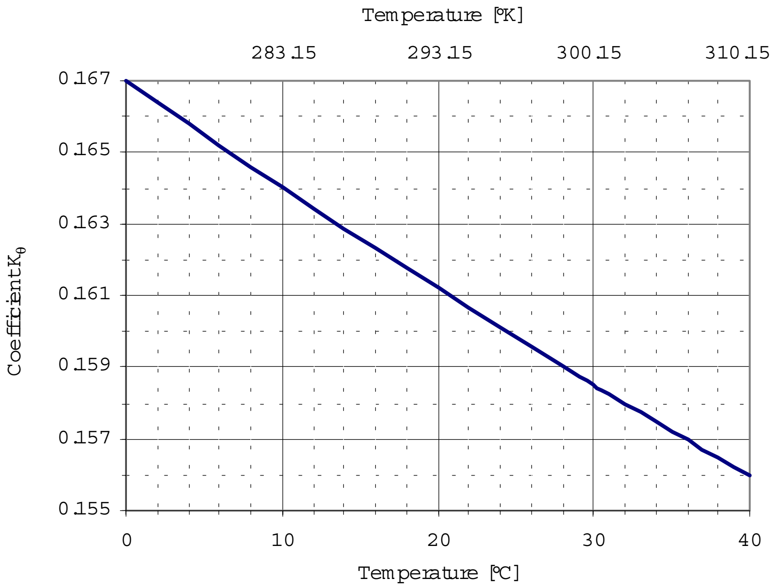


Figure 6.2 Value of K_θ (used in the reverberation time equation) versus air temperature.

6.8 ACOUSTIC ZONE VS THERMAL ZONE

When a building is modelled, a thermal zone generally corresponds to an enclosure delimited by building elements, in which some physical properties, such as the air temperature, are uniform in that delimited volume: for instance, an office room might be modelled as a thermal zone. In this case, the acoustic boundaries correspond to the thermal zone boundaries. The air volume used to assess the reverberation time is equal to the volume delimited by the thermal zone.

For a larger space, such as an atrium, the enclosure might be separated into several smaller thermal zones to assess the distribution of air temperature as a function of height. The volume is then segmented in a superposition of thermal zones. In such cases, the surface contiguous to two thermal zones is defined as a 'fictitious' element that does not have properties (hygro-thermal, environmental impacts factor, etc.). Thus, the utilisation of a fictitious surface in the model does not influence the thermal analysis.

From the viewpoint of room acoustics, the reverberation of the atrium is not the sum of the reverberation time of all thermal zones. To assess the reverberation time of such a large space, made of several thermal zones, the philosophy is to record for the fictitious surface absorption coefficients equal to zero at each frequency. Thus the reverberation time can be calculated by taking into account all the thermal zones as shown in Figure 6.3.
With this approach, the air volume used for the reverberation time calculation is equal to the sum of the thermal volume and the surface included in the calculation corresponds to the surfaces of all thermal zones. And as the fictitious surface does not absorb sound by definition, the contiguous surfaces are not taken into account in the calculation of the reverberation time.

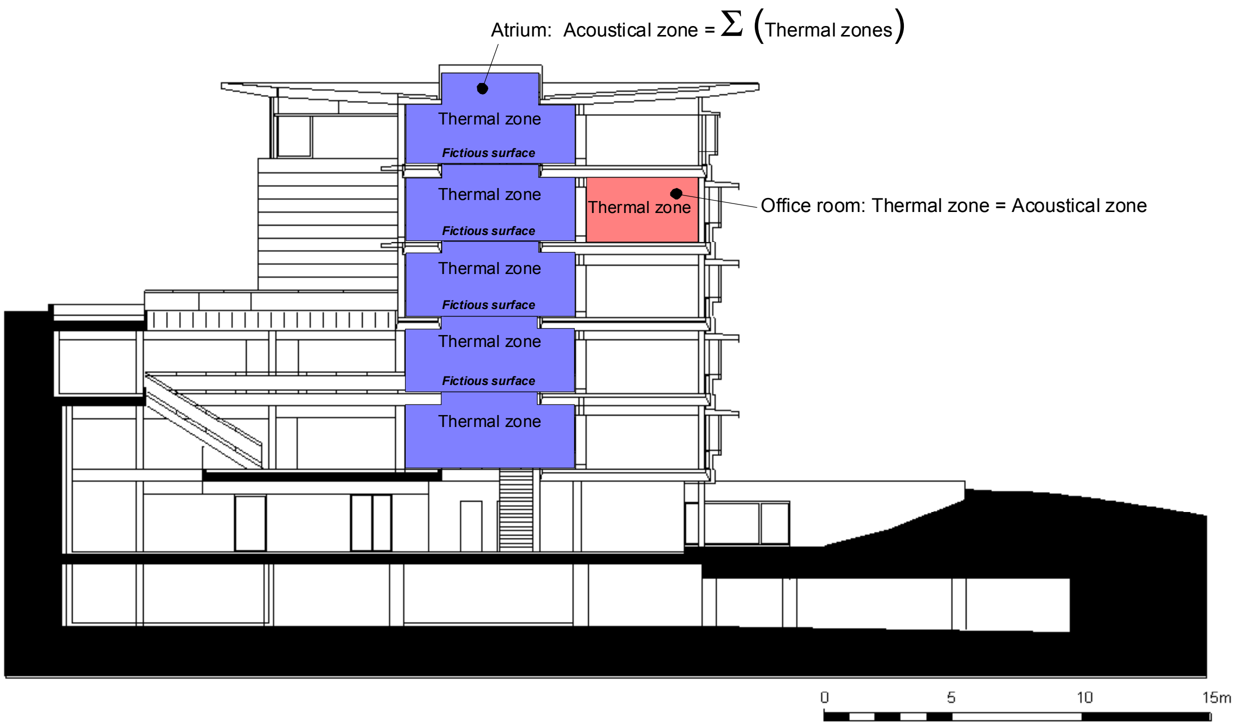


Figure 6.3 Thermal and acoustic zone representation in the case of an office room and an atrium.

When the aperture between two zones becomes small compared to the contiguous surface area, then the zones should be regarded as coupled spaces. In that case, the reverberation time calculation as proposed previously will not provide accurate results. Future developments might consider improving the calculation of such coupled spaces based on methods such as proposed by Jouhaneau [Jou1997].

6.9 ROOM ACOUSTICS INTERFACE

Figure 6.4 shows the interface of the room acoustics module implemented in ESP-r. When loaded, this module first reads the geometry model of the project (*EOS.cfg*) and the corresponding BCF file (*EOS.bcf*), which holds the information of the corresponding construction. Then it reads the occupants and piece of furniture information (*EOS_Aco.aco*), which is stored in an external file (interested readers can find the format description in Appendix O). Figure 6.4 also shows the procedure to perform a reverberation time assessment that starts with the selection of the zone(s) to analyse within the list of available zones in the project. For each selected zone (*F3_318* in the example illustrated in Figure 6.4), the module returns the list of the zone characteristics (Volume, floor area, etc.) and the related surfaces attributes (surface name, composition and net area). For instance, the selected zone has a volume of 79.93 m³ and is composed, among other, of a surface named *318_P3* with an area of 30.74 m² and made of a construction named *F-P_down*. Before the reverberation time calculation is initiated, the options listed in Table 6.3 can be modified.
In the example illustrated in Figure 6.4, the results obtained with the Sabine equation are displayed for the one-third octave band. It includes the equivalent area for the surface boundaries (*318_P3* to *high_win*), the occupants in the zone (1 person *Standing*), the furniture piece in the zone (*10 upholstered chairs*) and the enclosed air. Finally at the bottom of the textual feedback, the corresponding reverberation time per one-third octave band is given.

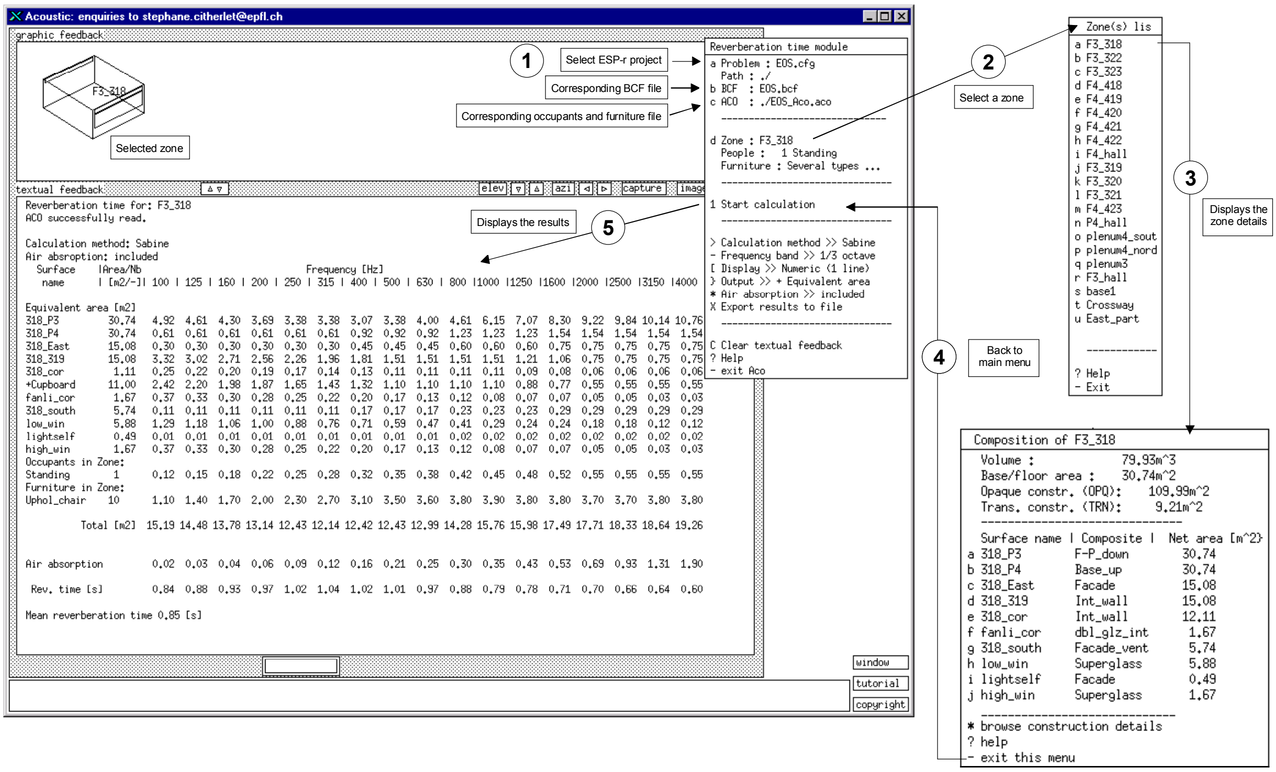
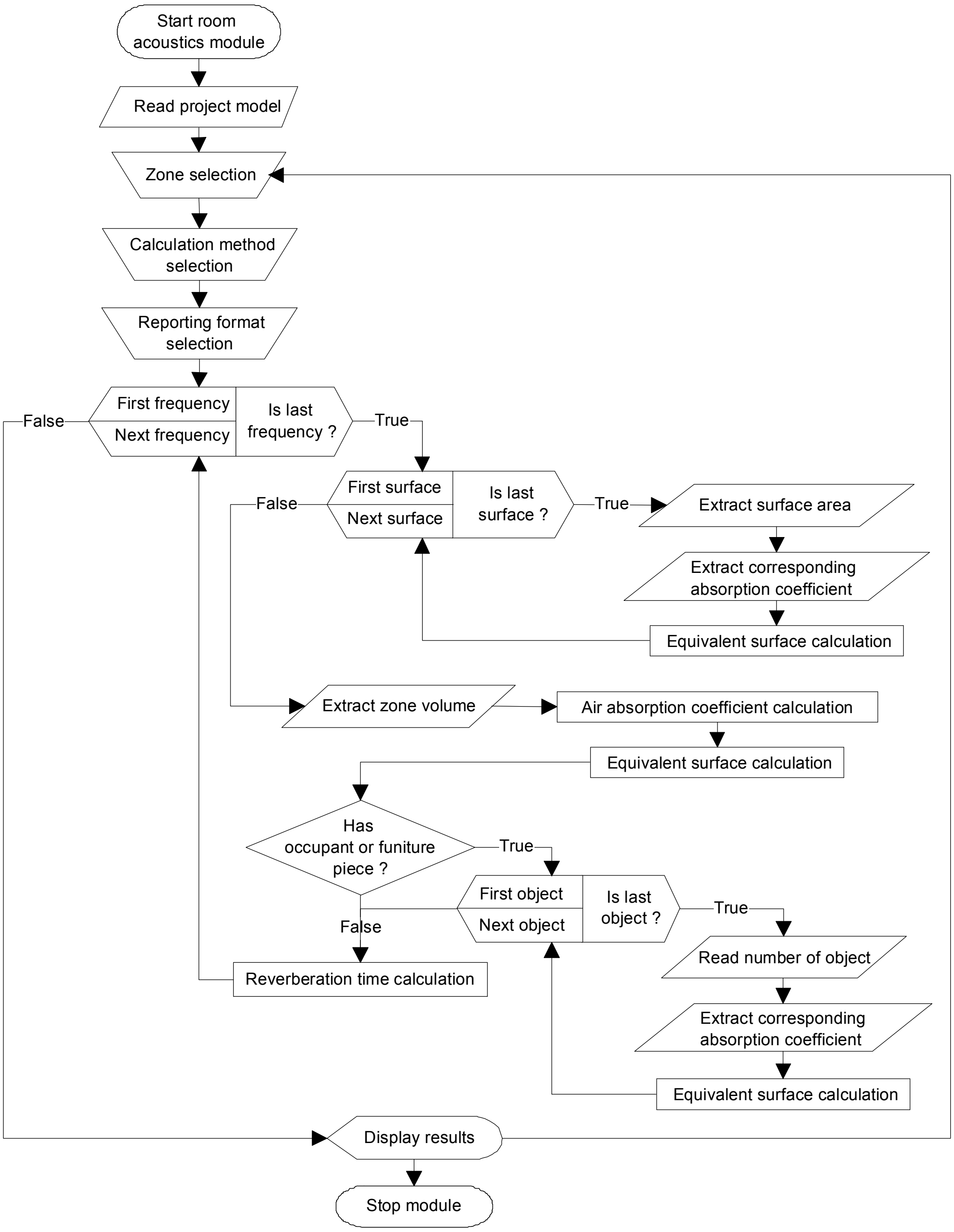


Figure 6.4 Room acoustics interface.

Options	Effects
`> Calculation method >> Sabine`	Selection of the reverberation calculation method: Sabine, Eyring and Millington, generally calculated separately. It is also possible to perform the calculation for the three methods concurrently.
`- Frequency band >> 1/3 octave`	Selection of the octave band for which the reverberation time is assessed: either one third or one octave band.
`[ Display >> Numeric (1 line)`	Selection of the result display format
`} Output >> + Equivalent area`	Selection of the information to display. The following possibilities are offered: A) The reverberation time B) Equivalent area + reverberation time C) As B) + absorption coefficients
`* Air absorption >> included`	Define whether or not the air absorption must be included for the reverberation assessment. Although it should be always included, discarding it in the calculation permit appraising its influence.
`X Export results to file`	Define a file to which the results are exported

Table 6.3 Room acoustics calculation options.

Once the desired calculation and reporting options have been selected, the reverberation time calculation can be initiated. First of all the geometry model of the selected zone(s) is scanned. For each detected surface, the corresponding absorption coefficient set is used to determine the equivalent surface area according to the selected calculation method as shown in Figure 6.5.



(Acoustic calculation flow chart (implemented).flo)

Figure 6.5 Flow chart of the reverberation time calculation.

At the end of the iterative process the total equivalent area of the boundaries is obtained. Then the occupant, furniture and air absorption contributions are included to obtain the total equivalent absorption area, from which the reverberation is calculated.

CHAPTER 7

INTEGRATED CASE STUDY

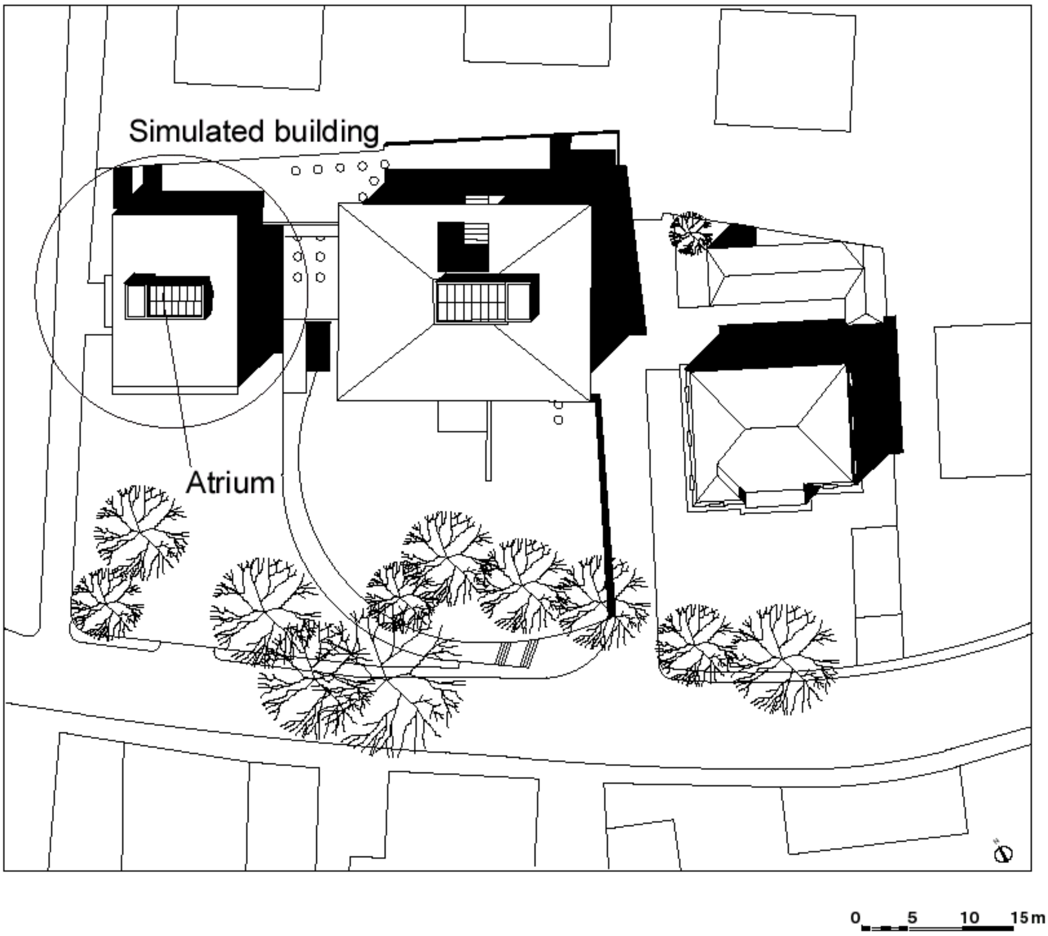
The previous chapters have described in detail the necessity, the elaboration and finally the implementation of a data model that enables a multiple-view assessment of building performance. The present chapter, which is the final step of this work, is dedicated to the utilisation of all the developments undertaken up-stream. It presents the overall performance obtained for an office building as predicted by ESP-r enhanced with the development undertaken in this dissertation. The simulation results have been compared with measurements monitored in the building during the post-occupancy phase. This chapter does not have the pretension to validate the simulation, but rather to analyse the conformity of the simulation results with the measurement results and to see if the integrated simulation approach developed in the present work was applicable.

7.1 THE *ENERGIE OUEST SUISSE* BUILDING

The headquarters of Energie Ouest Suisse (EOS), one of the major electricity producing companies in Switzerland, was selected as a case study because: (1) it had been widely monitored during the European project 'Daylighting Design of European Building' [Sca1997b] and (2) its proximity, which permitted extending the monitoring to domains that had not been analysed previously.

The EOS building is a four-story office building, constructed between 1994-1995 in the city centre of Lausanne in the southwestern part of Switzerland on the Geneva lake shore (Latitude 46.32 N, Longitude 64.48 E, altitude 492 m). It is situated on a sloping site with a southwest orientation and consists of two building blocks linked by an entrance platform on the ground floor as shown in Figure 7.1. The building comprises about 10 office rooms per floor (400 m² per floor), which corresponds to a total gross area of 5900 m². The majority of the office rooms are located along the main building facade.

External light shelves are installed above a row of windows for office rooms located on the south facade as shown in Figure 7.2. The design of the light shelves was carefully studied before building construction, with the aim of optimising their geometry (slanting angle) and their photometry (type of material and specularity) by means of scale model simulation [Chu1994]. Finally, a central atrium is located behind the office rooms and provides them with daylight from the back. A complementary architectural description of the EOS building can be found in [Bus1996].



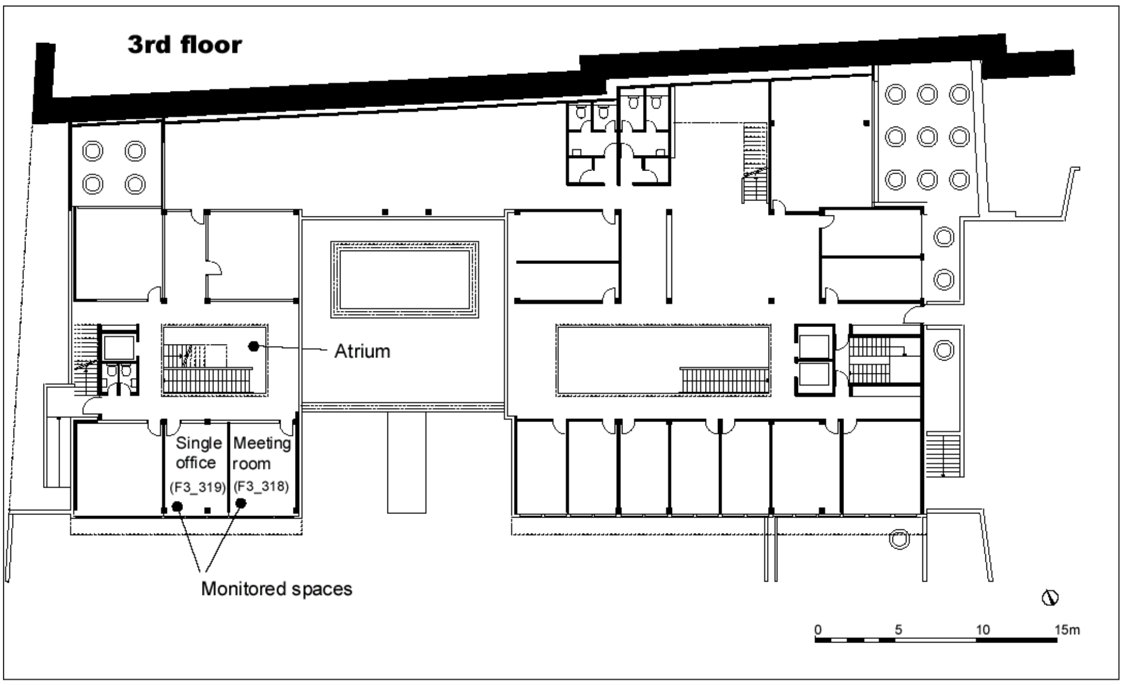


Figure 7.1 Plans of the EOS building.

Figure 7.2 Different views of the EOS building.

7.2 ROOM DESCRIPTION

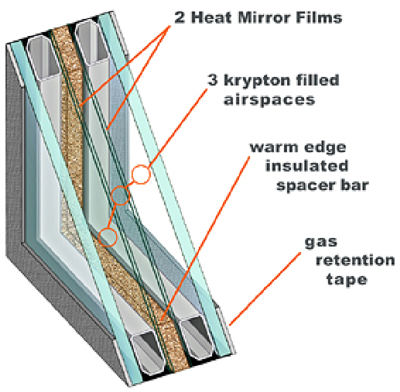
Each office room is occupied by one person, and has a width of 5.7 m, a depth of 5.2 m and a height of 2.6 m. The floor is made of a 24 cm height plenum with a fitted carpet and the ceiling has been given a roughcast finish applied directly on the concrete slab in order to improve the thermal inertia. The partition walls are made of steel sheeted plasterboard with 5 cm mineral wool insulation. The office room is provided with daylight mainly from the facade openings, which have a glazing area of 4.4 m². In addition, an opening of 1.2 m² is located on the backside of the room, providing daylight to the room through the central atrium as shown in Figure 7.2. The glazing ratio of an office room is equal to 0.19: the main part of the glazing area is located on the main facade (4.4 m^2).

7.2.1 Windows

The EOS building uses super-insulated glazing systems (Superglass from Sofraver Ltd, Switzerland) for the facade. They are made of double clear float panes filled with Krypton, with two low-emissivity (ε = 0.14) coating films tight in the gas gap (4/10/3/10/4 mm) as shown in Table 7.1.

<table>
<tr><th>Glazing components</th><th>Description</th></tr>
<tr><td>

External glazing system



(Superglass.tif)

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Superglass is made of two 4 mm clear float panes with two low-emissivity coated films of 0.5 mm tight between the panes and filled with Krypton.

Spacer : Aluminium

Shading : External fabric blind
+ Alu. light shelf

Frame : PVC (Polyvinyl chloride)

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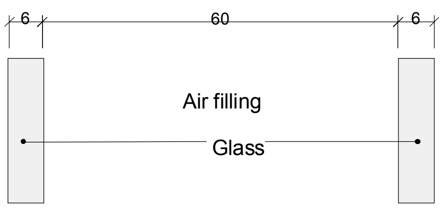
Internal glazing system (thickness in mm)



</td><td>

Double insulated glazing composed of two clear float panes of 6 mm and an air gap of 60 mm.

Spacer : Aluminium

Shading : None

Frame : PVC (Polyvinyl chloride)

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</table>

Table 7.1 Glazing system of the EOS building.

Properties	EOS glazing types	
	External (Facade)	Internal (back wall)
Layers thickness [mm]	4/10/3/10/4	6/60/6
Gas filling	Krypton	Air
Low emissivity film	2 films tight in gas	-
Film emissivity [-]	0.14	-
Glass emissivity [-]	0.84	0.84
Overall, normal incidence visible transmittance τ [-]	0.62	0.78
Overall, normal incidence solar transmittance g [-]	0.46	0.69
U-value [W/m²K]	0.77	2.85

Table 7.2 Optical and thermal properties of these glazing.

The internal windows (between the office and the atrium) consist of double clear float glass (6/60/6 mm) filled with air. The glazed area of the back wall is small (1.2 m^2), which corresponds to a poor window fraction (0.09). The window has a PVC frame and aluminium spacer. An external fabric blind is used as a movable shading system for the facade window. Table 7.2 summarises the overall thermo-optical performance of these glazing systems.

7.2.2 Artificial lighting

There are no lighting fixtures on the office ceiling. Each desk is equipped with a floor luminary in direct-indirect lighting mode. Each luminary uses 4 compact fluorescent lamps (4 x TL36 W). Switching between luminaries is possible from the entrance door and from the work desk. There is no dimming function on the luminary either daylight responsive or user controlled.

7.2.3 Ventilation/infiltration

There is no mechanical ventilation system in the office rooms. The building is naturally ventilated through transversal ventilation in the office and the openings located at the top of the central atrium. A large meeting room located in the core of the building is the only space equipped with a mechanical ventilation system, which is used only when the space is occupied.

7.3 COMPUTER MODEL

In order to set up a realistic computer model, it was necessary to find and gather relevant information on the building (geometry, constructions, usage, etc.). The computer model of the EOS building was developed on the following basis:

- Geometric information extracted from drawings, provided by the architects *Richter and Dahl Rocha*, Avenue Dapples 7, CH-1006 Lausanne (Switzerland)
- Physical properties were determined on the basis of detailed architectural drawings, manufacturer data and engineering handbooks.

With the help of these sources, a detailed computer model was set up, which represented the last two floors of the southwest core of the building. The whole model consists of 21 interconnected thermal zones, as shown in Figure 7.3.

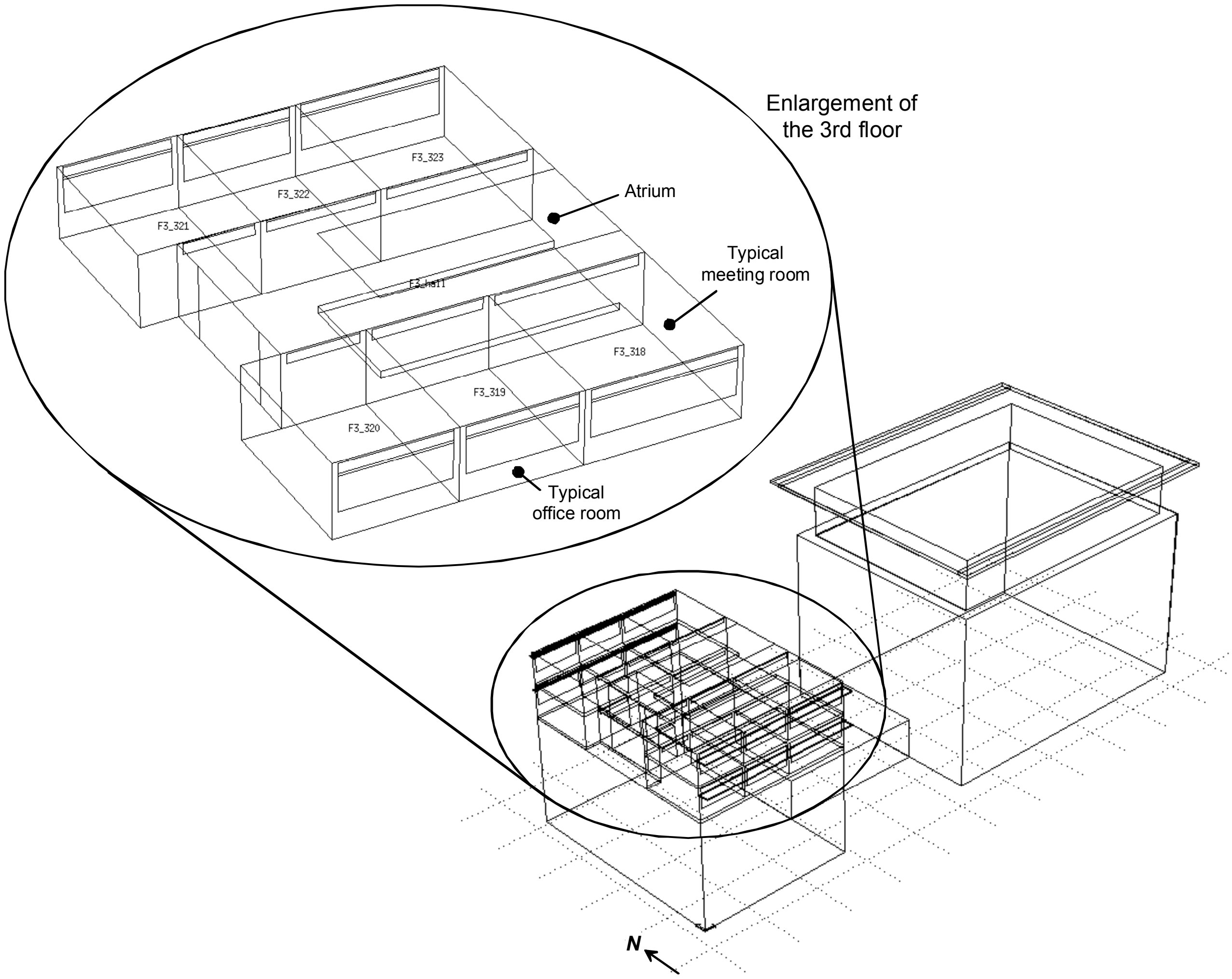


Figure 7.3 Computer model representation of EOS building. (Model+.dsf)

Eighteen zones are located on the second and third floor of the western part of the building (see Table 7.3). They correspond to the offices, circulation-atrium and the plenum floor. The remaining zones complete the building shape. A typical office situated on the third floor (F3_318) was selected for the daylight, room acoustic, thermal and visual comfort assessment and was monitored for this purpose. The third and fourth floor underwent an energy and environmental impact assessment.

Zone	Volume [m^3]	Floor area [m²]	Description
F3_318	79.9	30.7	Meeting room in south part of third floor. Typical small meeting room (see Figure 7.3)
F3_319	61.8	23.7	Office in south part of third floor. Typical single office room (see Figure 7.3)
F3_320	61.8	23.7	Office in south part of third floor
F3_321	61.8	23.7	Office in north part of third floor
F3_322	61.8	23.7	Office in north part of third floor
F3_323	79.9	30.7	Office in north part of third floor
F3_hall	227.2	84.1	Circulation area of the atrium on third floor
Plenum3	51.7	207.1	Raised floor on third floor
F4_418	79.9	30.7	Meeting room in south part of fourth floor
F4_419	61.8	23.7	Office in south part of fourth floor
F4_420	61.8	23.7	Office in south part of fourth floor
F4_421	61.8	23.7	Office in north part of fourth floor
F4_422	61.8	23.7	Office in north part of fourth floor
F4_423	79.9	30.7	Office in north part of fourth floor
F4_hall	227.2	84.1	Circulation area of the atrium on fourth floor
Plenum4_south	19.5	78.3	South part of raised floor on fourth floor
Plenum4_north	19.5	78.3	North part of raised floor on fourth floor
P4_hall	12.6	50.5	Central part of raised floor on fourth floor
Base1	2310.2	249.7	Ground level, first and second floor
Crossway	555.6	158.7	Cross-way between east part and west part
East_part	6776.2	453.2	East part of the building

Table 7.3 Modelled zones of the EOS building.

7.3.1 Office rooms occupancy

It is assumed that offices are occupied by one person from 7 a.m. to 6 p.m. during weekdays. During the weekend and vacations, the room is not occupied. For the simulation, each office has an occupancy heat load of one person doing light work, which corresponds to 100 W of sensible heat and 40 W of latent heat according to the CIBSE data ([CIBSE1986] p. A1-4).

7.3.2 Constructions typologies

According to the architect's drawings, the opaque construction types presented in Figure 7.4 have been considered. It should be noted that the supporting bars of the plenum have not been explicitly represented, but have been included as a non-thermal layer in the construction to be accounted in the environmental impact assessment.

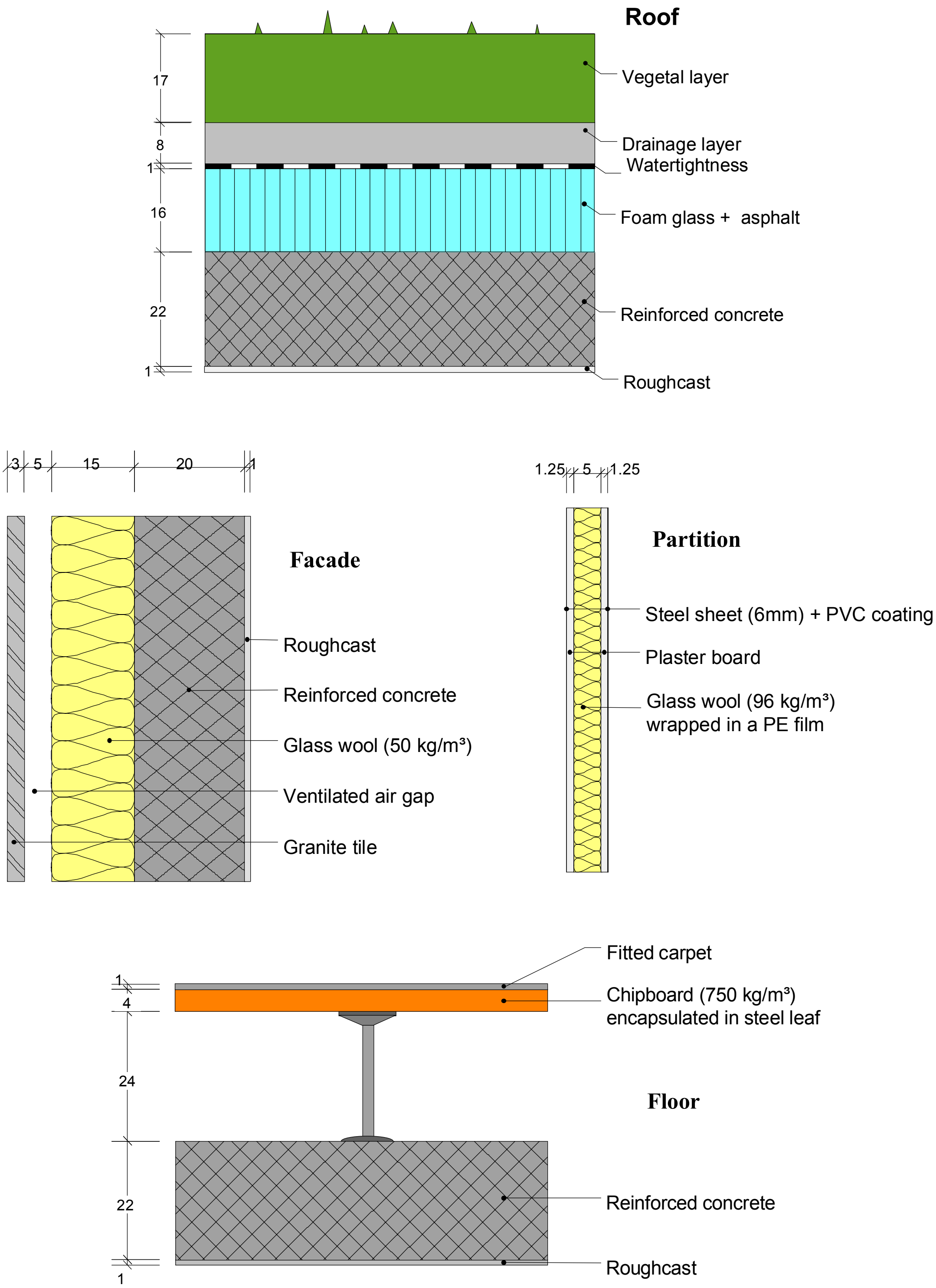


Figure 7.4 Opaque constructions of the EOS building used in the ESP-r model (thickness in cm).

To improve the accuracy of the simulation, both external and internal glazing systems were explicitly modelled (each pane). On the other hand, the frame and spacer were not explicitly defined in the geometry model of the EOS building. The window area in the computer model corresponds to the transparent area of the window. This simplification is acceptable, as the frame does not impact significantly on the annual energy consumption, because its U-value is comparable to the U-value of the glazing system. However, the frame and spacer were included in the glazing constructions as a non-thermal layer, which means that they are accounted in the environmental impact calculation. All the physical properties of the material used in the computer model of the EOS building can be found in Appendix Q.

7.3.3 Heating

The building is equipped with a central gas heating plant, which provides heat to the whole building. The heat is distributed through water radiators, located in each office. The set-point temperature is 20 [°C] during the occupied period, and an 18 [°C] setback is applied during off-hour periods on weekdays and during the weekend.

7.3.4 Ventilation/Infiltration

No flow network was set up, but ventilation and infiltration was defined as a constant air change rate. A constant infiltration rate of 0.1 [h^{-1}] was assumed during the whole year in the office room. During the transient and summer period, an air change rate of 2 [h^{-1}] was assumed during the working hours and of 5 [h^{-1}] otherwise, to take into account the cross ventilation used for night cooling.

7.3.5 Artificial lighting

The office rooms have no ceiling lighting fixtures but are equipped with one floor luminary per working place, each one equipped with a (4 x 36) W compact fluorescent tubes with a 45% radiative and 55% convective heat gain ([CIBSE1986], p. A7-4). The luminary is at 3 metres from the window, near the working place. A hand switcher controls each luminary. As there was no dimming luminary, the artificial lighting simulation was performed with the daylight factor profile obtained from the daylight analysis. These data, as the visual comfort analysis, were assessed with the Radiance model generated by ESP-r. An on/off control strategy with a set point of 500 [lux] illuminance at the working place was assumed ([CIBSE1986], p A7-5 or [SIA1995b], Annex B) from 7 a.m. to 6 p.m. during the weekdays and nil otherwise, to simulate the occupant behaviour.

7.3.6 Climate

Thermal simulation was carried out on the basis of an hourly time step simulation using the Lausanne climate retrieved from Test Reference Years (TRY) generated with *Meteonorm* [Rem1997]. The corresponding extreme and average monthly temperature are listed in Table 7.4.

Temperature [°C]	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Maximum	11.1	11.9	17.2	17.9	26.3	28.7	31.8	32.8	29.1	19.4	14.5	13.2
Average	1.7	2.3	6.0	8.9	13.6	16.8	20.5	19.9	16.1	11.4	6.0	3.4
Minimum	-5.9	-7.6	-3.6	-2.7	2.3	7.6	12.1	9.9	7.0	4.7	0.9	-3.0

Table 7.4 Extreme and average monthly temperature for the Lausanne climate.

The annual energy consumption was extrapolated based on a dynamical simulation performed over three typical weeks, which are defined in Table 7.5.

Period	Winter	Summer	Tansitory
Typical week	22nd to 28th January	10th to 16th July	9th to 15th April
Typical day	27th January	14th July	14th April

Table 7.5 The three typical periods of the Lausanne climate selected for use in simulation.

To select these weeks, the year was split into three different periods on the basis of degree-days (12/20 °C): winter, transient (spring and autumn) and summer. A typical week was selected for each period as representative of the climate throughout the period. The three weeks were chosen after analysis of the hourly weather data files on the basis of the solar radiation and ambient temperature. The annual energy consumption was extrapolated through weighting of the consumption of each typical week by the degree-days of the corresponding period.

7.4 ASSESSMENT OF THE BUILDING PERFORMANCE

Once established, the computer model was used for energy, lighting, room acoustics, environmental impacts and occupant comfort analysis. Building performance indicators were chosen in order to highlight the building domains listed in Table 7.6.

Domains	Indicators
Energy consumption	• Maximum power capacity • Annual energy consumption
Thermal comfort	• Predicted Percentage of Dissatisfied
Daylighting availability	• Daylight factor profile
Visual comfort	• Visual comfort index
Room acoustic	• Reverberation time.
Environmental impacts	• Emissions of pollutants related to energy consumption • Emissions of pollutants related to the building construction materials

Table 7.6 Domains and corresponding indicators assessed.

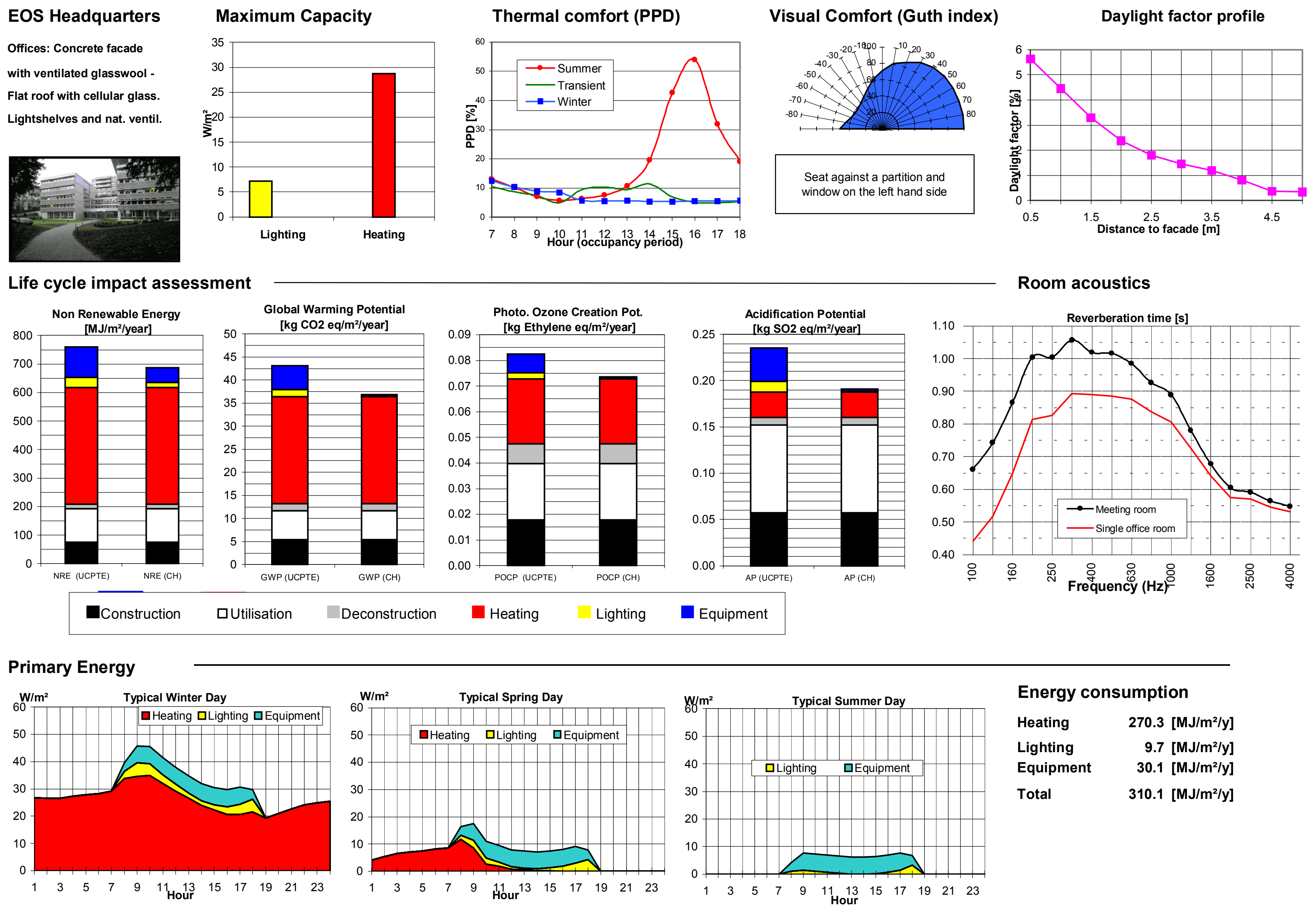


Figure 7.5 Integrated Performance View of the EOS building.

To have the possibility to bring together and display the disparate performance metrics that result from the different simulation views and thus ease result interpretation and variants comparison, these performance metrics were grouped together in a synthetic reporting format.
Clarke [Cla1998a] proposes the use of an Integrated Performance View (IPV), which is a collection of relevant performance metrics for energy consumption, thermal and visual comfort, and environmental impacts generated during the operation phase. The concept has been extended to include metrics related to the room acoustics and the environmental impacts of the building during its whole life cycle as shown in Figure 7.5. In the next sections, each performance indicator is analysed separately and if monitored data are available, the results are compared to in-situ monitored data.

7.5 ENERGY PERFORMANCE INDICATORS

The annual energy consumption for heating, lighting and equipment in the EOS building are listed in Table 7.7. The heating energy consumption of the EOS building is reasonable. This is not surprising when considering the solutions retained to reduce the heat loss through the shell and the absence of mechanical ventilation in most of the building. The heating energy consumption of the EOS building, averaged over the first three years of operation, is equal to 255 [MJ/m² y]), which corresponds to a difference of about 5% with the simulated results.

Source	Fuel	Useful energy delivered		Monitored
		kWh/m²/y	MJ/m²/y	MJ/m²/y
Heating	Gas	75.1	270.3	250.6
Lighting	Electricity	2.7	9.7	42.5
Equipment	Electricity	8.4	30.1	

Table 7.7 Normalised Performance Indicator of the EOS building.

For practical reasons, it was not possible to monitor the specific annual electricity consumption of the lighting and the equipment separately and only the total electricity consumption was measured. The electricity delivered for the whole EOS building equals 42.5 [MJ/m²/y], while the simulation results estimation is about 39.8 [MJ/m²/y] (one quarter for the lighting and three third for the equipment). The interpretation of the closeness of these values is not straightforward. It has been noticed that most of the occupants are relatively intensive computer users and the illuminance level at working place was generally lower than the 500 [lux] used in the computer model for a work place in an office building and was more likely near to 300 [lux] or even lower for certain occupants. Thus, the simulation results for the lighting consumption, and correspondingly the total electricity consumption, should have been overestimated, which is not the case. It should be kept in mind that the electrical energy consumption includes the artificial lighting and the equipment. Therefore, if the lighting consumption is lower than estimated, the equipment electricity consumption should in reality be higher than simulated. This was confirmed during the post-occupancy visit, during which it was observed that several single office rooms had been equipped with a personal printer and/or a second computer. Furthermore several unexpected electrical devices such as battery chargers for mobile phones or music players that were not taken into account in the simulation have also been observed. This supplementary consumption of electricity may have compensated the reduction of the artificial lighting consumption obtained in the simulation.

7.6 MAXIMUM POWER CAPACITY

The maximum power capacity of the building's technical installations is the maximum power required by the different energy appliances in the building, which for the EOS building corresponds to the lighting and heating equipment. The simulation returns a specific connected lighting power of 7.2 [W/m²], which is lower than the 9.4 [W/m²] that have been installed in the EOS building as shown in Figure 7.6. On the heating side, the EOS building is equipped with a gas boiler that supplies 39.3 [W/m²], which is not comparable to the 28.7 [W/m²] obtained by simulation. The differences in the lighting and thermal power capacity probably originate in the habit of lighting and heating engineers to overestimate the required maximum capacity by about thirty percent.

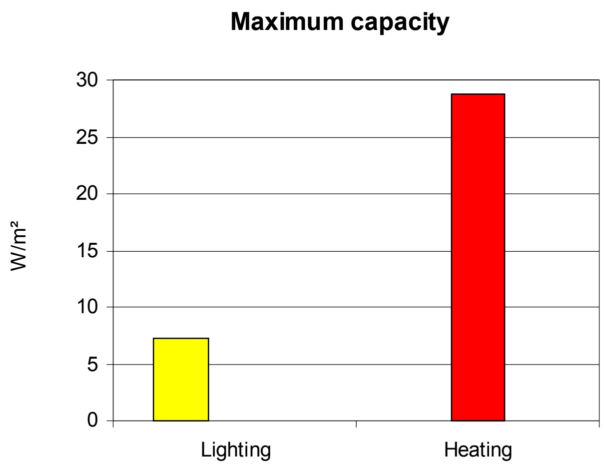


Figure 7.6 Maximum power capacity for lighting and heating (EOS building).

7.7 PRIMARY ENERGY CONSUMPTION DURING TYPICAL DAYS

Hourly primary energy profiles for lighting, heating and cooling of the whole building are expressed as hourly profiles for each typical seasonal day, as shown in Figure 7.7. The peak demands for each typical day can also be retrieved from these profiles. As can be seen, it occurs at the beginning of the occupancy period. As the working hours pass, and the internal gains (energy generated by occupant(s), lighting and equipment) and the solar gains freely heat the office room, the required heating energy is reduced.

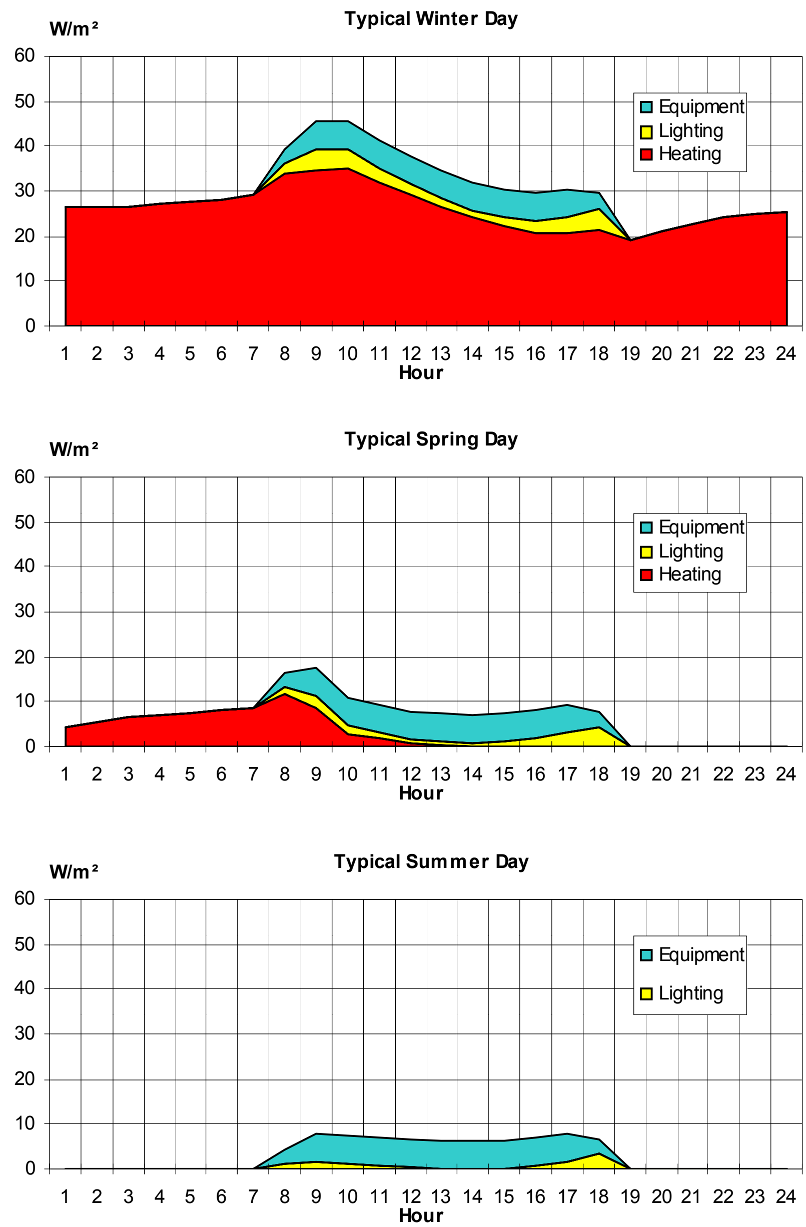


Figure 7.7 Primary energy profile for three typical days (EOS building).

7.8 THERMAL COMFORT

The thermal comfort is expressed by the predicted percentage of dissatisfied (PPD) as defined in the ISO 7730 standard [ISO1994b]. The PPD gives the percentage of people likely to feel too hot or too cold in a given thermal environment. The PPD is influenced by the thermal properties of the room, such as the air and surfaces temperature, air humidity or wind velocity, but also by the clothing (thermal resistance) and activity (metabolic rate) of the occupant. In this study, it has been calculated in a south facing typical office room with the occupant clothing depending on the season and a metabolic rate corresponding to a sedentary activity as listed in Table 7.8.

Season	Clothing [Clo]	Metabolic rate [Met]
Winter	1	1.2
Transient	0.85	1.2
Summer	0.5	1.2

Table 7.8 Clothing and metabolic rate used to assess the thermal comfort in the typical office.

The corresponding PPD in the typical office room during the occupancy period, for each typical seasonal day is given in Figure 7.8. The ISO standard recommends the PPD to be lower than 10% for an acceptable thermal comfort. But due to individual differences, it is impossible to specify a thermal environment that will satisfy everybody and thus there is always a 5% of dissatisfied people whatever the thermal environment is.

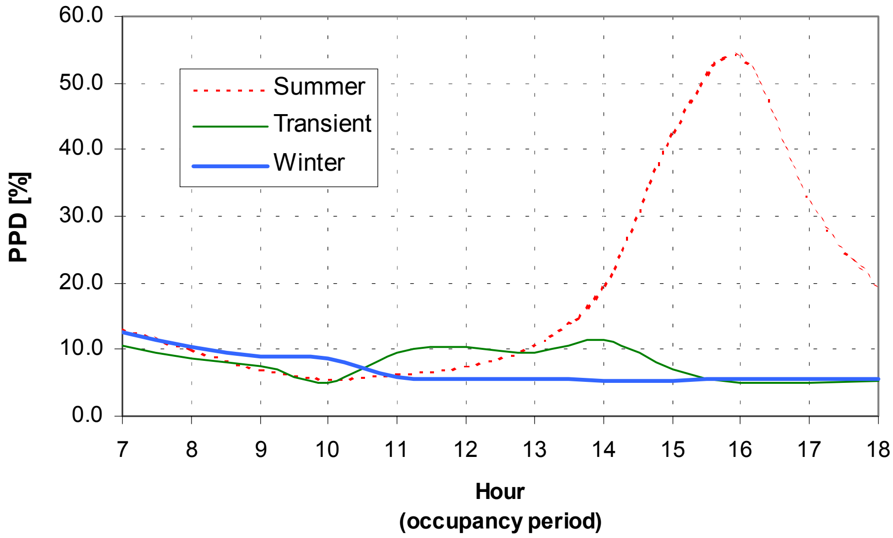


Figure 7.8 Thermal comfort assessment in a typical office for three typical seasonal days.

During the winter and transient period, the thermal comfort is good as can be seen in Figure 7.8. During the summer period, the occupant experiences overheating at the end of the day, when the sun is low on the horizon (west). The light shelf of the typical office room (facing South) does not stop direct sun radiation. The external fabric blind is not sufficiently efficient to stop the direct sun radiation and the upper part of the external window is not equipped with a shading system, which leads to unacceptable solar gains in the office, which has a medium thermal inertia. A post-occupancy evaluation of the EOS building, carried out by means of a questionnaire distributed to 33 building users confirmed that one third experience overheating *often* and one third *sometimes* during the summer period [Sca1997a].

7.9 DAYLIGHTING

The level and distribution of daylight factors (ratio between internal and external horizontal illuminance) has been used as an indicator of the impact of daylighting inside the building. A daylight factor profile is calculated for the representative office room. The profile is determined at the level of the work plane (0.75 m above the floor), perpendicularly to the window and in the middle of the room. The daylighting factors were measured by Michel (see [Sca1997b]) under overcast skies according to the procedure recommended by the CIE [CIE1970]. The daylight factor profiles of the monitored room and the corresponding simulation results are given in Figure 7.9. As can be observed, the computer simulation results are consistent with the in-situ measurements.

Compared to an office room without the light shelf, a more uniform illuminance distribution is achieved in the EOS office room, and thus lower luminance contrasts. The post-occupancy evaluation of the EOS building has confirmed the positive appreciation of the daylighting features of the building.

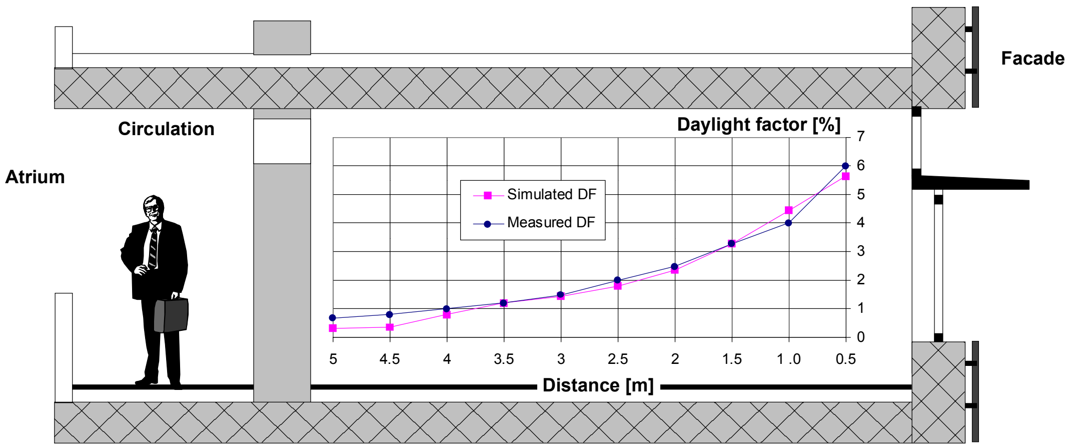


Figure 7.9 Measured and simulated daylight factors (DF) distribution in a typical office room of the EOS building. (flj.dsf)

The DF of 0.5% in the rear of the office is comparable to the DF that would be obtained in the same office without the internal window. Therefore, this opening in the back wall does not contribute significantly to the illuminance in the rear of the office. This is due to the low glazing fraction of the opening and to the presence of the circulation of the upper storey, which plays the role of horizontal eaves and thus reduce the supply of daylight from the atrium.

7.10 VISUAL COMFORT

The visual comfort has been estimated in a typical single office room. Among the different indicators that could be used, the J-index [Mey1994] is probably the most suited to assess the visual comfort during a specific task (computer use, reading, etc.) and can be assessed with Radiance. Unfortunately, though, the use of that J-index requires the adding of a visual target in the geometry scene that is not yet automatically generated by ESP-r when it creates a Radiance model from its own model. Although the object could be added manually in the Radiance file, it has been decided to use another indicator that does not require manual completion of the Radiance model, to be consistent with the approach developed in this work.

Despite some limitation, the Visual Comfort Probability (VCP) [Gut1963] has been selected because it has been widely accepted and correspond to a conventional comfort appraisal, expressed through the percentage of persons satisfied by the visual environment when looking from a particular point of view in a given direction.

In the studied single office, the view position corresponds to the occupant seat, which is leaning with his back against the East partition. The VCP has been assessed with a view direction scanning from left (-90°) to right (90°) as shown in Figure 7.10. As can be seen, the VCP is below the recommended 70%, when the occupant looks in the direction of the facade, due to the glare sources generated by the openings. The more the view is oriented in the direction of the rear partition, the higher the VCP. A post-occupancy sounding out of opinion has confirmed that tendency. Some intense computer users (secretaries) have even partly obstructed the windows with an opaque screen to reduce the glare sources.

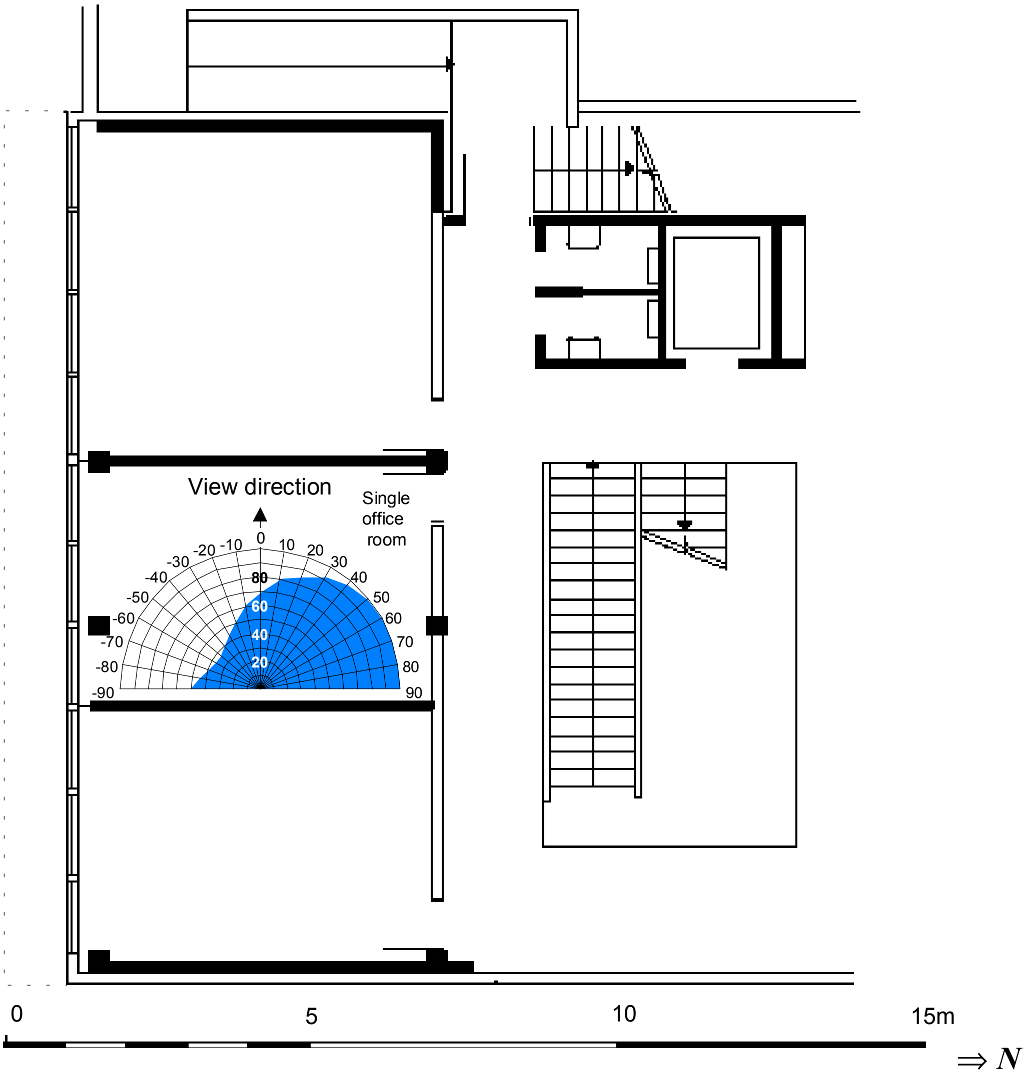
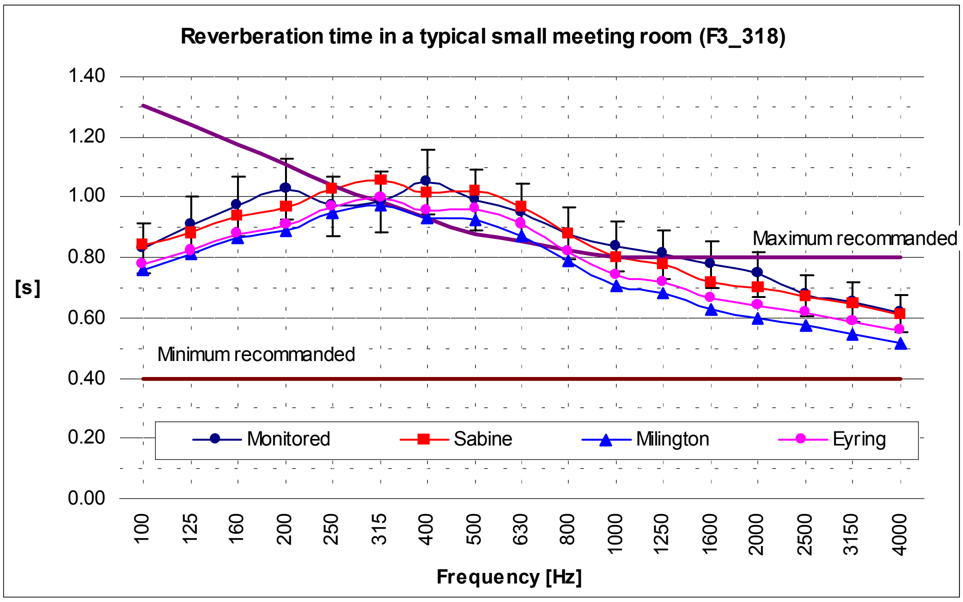


Figure 7.10 Visual Comfort Probability (VCP) in a typical single office room. (test VCP.dsf)

For the interested person, a detailed glare source analysis and a visual comfort assessment using the J-index has been undertaken for the same single office by Compagnon [Sca1997b] within the framework of the European project *Daylighting Design of European Buildings*, but using a specific Radiance model.

7.11 ROOM ACOUSTICS

The reverberation time was calculated for the typical single office room and meeting room based on the Sabine, the Eyring and the Millington method. The monitored profile was established according to the procedure recommended by the ISO [ISO1975b]. These calculated and monitored profiles are included in Figure 7.11.



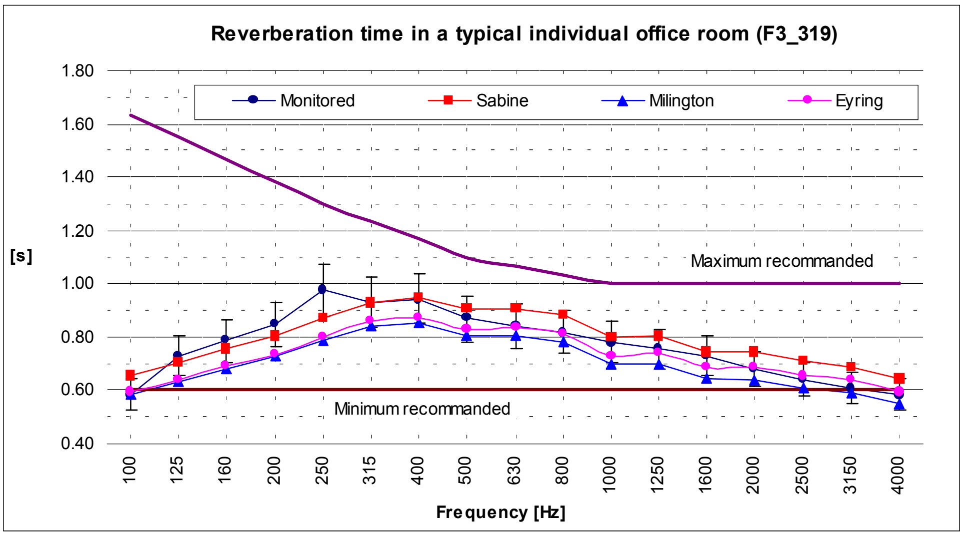


Figure 7.11 Monitored and calculated reverberation time for a meeting room (top) and a individual office room(bottom) of the EOS building. (Vérif Aco model 318(9).xls

The monitored profile corresponds to the mean profile obtained by measurement at three different locations in the room and the error on the measured profile has been estimated as 10%. As emphasised in the chapter related to the room acoustics, the accuracy of the reverberation time assessment depends on the quality of the absorption coefficients used for the calculation. Except for the floor, the absorption coefficients of the different constructions have been extracted from publications. For the office floor, made of a plenum covered with a fitted carpet, the absorption coefficients had to be estimated, as no data was available. The Appendix P depicts how these coefficients were evaluated based on available coefficients for a wooden plenum and of a fitted carpet glued on a concrete slab.
Figure 7.11 includes also the recommended maximum and minimum reverberation time value extracted from [OFQC1989]. As can be seen, the reverberation time in the single office room is within the recommended domain. On the other hand, in the meeting room, the reverberation time is higher than the recommended value for frequencies between 250 et 1000 [Hz], which reduces the speech intelligibility as observed by the occupants.

Among the three methods, Sabine has predicted the best results. This is not surprising as this equation is the most suited for an average surface-absorption coefficient $\overline{\alpha}^{Sab} < 0.2$, which is the case in the single office room ($\overline{\alpha}^{Sab} \cong 0.14$) and in the meeting room ($\overline{\alpha}^{Sab} \cong 0.13$). This would not be the case if the ceiling was covered with an acoustic absorbent, which may be necessary in the meeting room to achieve the recommended reverberation time.

The reverberation time calculated in Figure 7.11 is representative for a zone air temperature of 26°C and a relative humidity of 60%, which correspond to the conditions observed during monitoring (summer day). To show the sensitivity to the room conditions of the air absorption at high frequency, Figure 7.12 displays simulated results obtained with the Sabine equation for two different periods of the year.

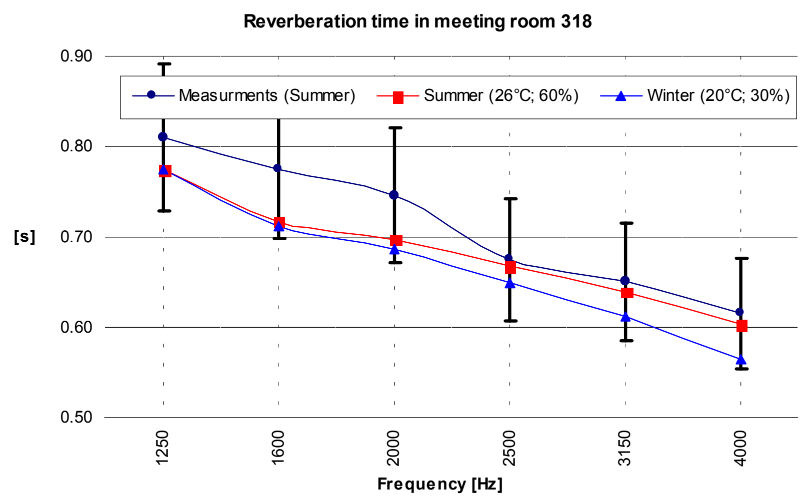


Figure 7.12 Influence of the air temperature and humidity on the reverberation time (Sabine's equation). (Vérif Aco_model-318.xls)

Below 1600 [Hz], the reverberation time is not affected by the air properties and can be neglected, but above that frequency, the air absorption becomes relevant. In the case of the small meeting room (80m³) shown in Figure 7.12, the reverberation time difference between the two air thermo-physical properties is about 8% at 4000 [Hz], which almost corresponds to the error range.

7.12 LIFE CYCLE IMPACT ASSESSMENT

The life cycle impact assessment of the EOS building presented in this section includes all the life cycle phases of all the materials defined in the eighteen zones that represent the second and third floor the building. It includes the intrinsic (building entity) and extrinsic (energy consumed for services) environmental impacts. The contributions to the intrinsic impacts are grouped into three major categories: construction, occupation, and deconstruction. The extrinsic contribution is segmented for each energy source consumed to provide the building services (heating, lighting and equipment).

For each indicator, the results are normalised per gross floor area and per year. The building life span was fixed to 80 years. To illustrate the impact difference according to the energy supply source, each indicator has two bin sets, one obtained with UCPTE-mix electricity (Euro) and the other with Swiss-mix electricity (CH) as shown in Figure 7.13. It emerges from the differentiation of the electricity origin, that environmental effects are lower with Swiss current because a major part of it is produced by hydraulic power plants. These results also show that when all the building phases are included in the impact assessment, the extrinsic and the intrinsic contributions are of the same order of magnitude.

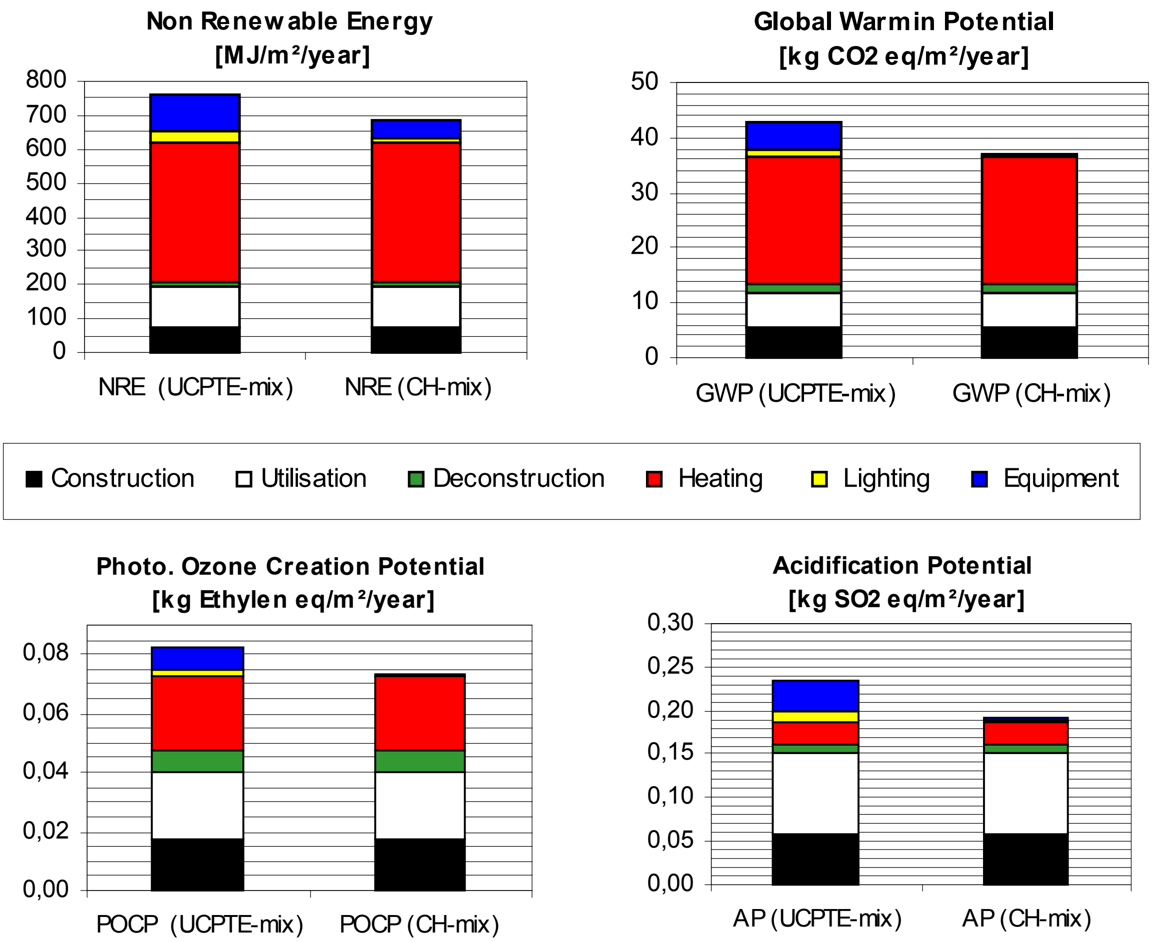


Figure 7.13 Environmental effects of the EOS building. (summary EOS.xls)(summary EOS.xls)

Among the intrinsic environmental impacts, the largest contribution is generated during *Utilisation*. This is not surprising as it encompasses maintenance and replacement (i.e. the sum of all downstream impacts generated by the replacement of a building element including its manufacturing, transport and assembly). During the building life span of the EOS building, all the construction materials except the reinforced concrete, is replaced at least once. For instance, the facade granite cladding is replaced only once, while the fitted carpet is replaced seven times. The sum of all the contributions generated for these material replacements is therefore not to be neglected.

As it can be seen in Figure 7.13, extrinsic contributions generate the major contribution of the NRE (73% for Euro and 70% for CH) and the GWP (69% for Euro and 64% for CH) for the EOS building. On the other hand, the intrinsic contributions generate the major contribution of the AP (68% for Euro and 84% for CH) and the POCP (58% for Euro and 65% for CH).

The only possibility to analyse the validity of the results is to compare them with published data. The system limits, the methodology and the data origins may vary strongly between studies, which makes a comparison difficult. Nevertheless, the LCIA of the EOS building is in agreement with several studies. For instance, the impacts of the manufacturing phase of the EOS constructions are similar to the data provided in [SIA1995a]. The NRE required to manufacture, transport and construct a building represents about 8% of the energy used to run the services during the building life time of this type of building in a Northern climate, which corresponds to the result obtained by Harris (8%) [Har1997] and Peuportier [Peu1999]for a concrete building. The impacts generated by the different transportation phases are for NRE and GWP ≈ 10% of the total impacts of the building (without operation), which is similar to the result obtained by Miller (12%) [Mil1997]. This fraction rises to 25% for POCP, for which no data have been found in the literature. For the LCIA, the EOS results are in agreement with [Gay1997] who studied a concrete building with similar system boundaries in a Swiss climate.

Compared to the other views, the LCIA assessment encounters more difficulty in gathering the necessary information. The availability of the environmental impact factors for construction materials, transport and material disposal is good. On the other hand, it was more difficult to obtain the material loss rate during transport and assembly, and the material elimination rate. This information was obtained from manufacturers and consultants, but a great variability has been observed depending on the sources. Nevertheless, comparison with other studies shows a good agreement of the results and therefore supports the assumption that the approach developed in this work is suitable for a comprehensive assessment of the environmental impacts generated during the building life.

CHAPTER 8

CONCLUSION

This work has demonstrated the feasibility of a multiple-view assessment of the building performance based on a single and integrated simulation application that relies on :

- The decoupling of the geometrical representation of the building and the description of the construction materialisation.
- The construction representation is structured by view, like a backbone is structured around vertebras. In the proposed representation, the included views are: hygro-thermal, optical, photo-colourimetry, room acoustics and environmental impacts.
- To be assessment method independent, the physical attributes for a particular view encompass a comprehensive set of elementary data, i.e. a list of attributes that are required by different assessment methods but cannot be derived from other attributes.
- To support a detailed life cycle impact assessment (LCIA), the environmental attributes are structured around a life cycle phase decomposition of the building life span, which includes manufacturing, transport, assembly, maintenance, replacement, deconstruction, and waste elimination as well as possible material loss during the different phases.

The model developed in this work has been implemented into ESP-r, an existing simulation application that is capable of modelling transient energy and fluid flows within combined building and plant systems. To achieve a holistic approach, its capabilities have been extended to support the assessment of room acoustics and the life cycle impact.

Finally, a case study analysis has shown the applicability of the developments presented in this document. The selected building is an office building located in Lausanne (Switzerland) for which a global assessment of the energy consumption, thermal and visual comfort, room acoustics and LCIA was undertaken. For each performance indicator, the simulation results were compared with in-situ measurements where monitored data were available. The simulated energy consumption, occupant comfort and room acoustics performance are in good agreement with measurement results. For the LCIA, the results are in good agreement with available publications.

8.1 FUTURE APPLICATION

At the data model level, the solution proposed in this work to represent the physical properties of a construction is more comprehensive than the description used in the STEP procedure and therefore could be proposed as an extension of this standard data model.

At single-view level, the implementation of a life cycle impact assessment into ESP-r enables a quick and automated assessment of the environmental impacts of a project. The elaboration of a model to assess the intrinsic environmental impacts allows a detailed appraisal of the contribution of each material and energy flow during the various building life cycles in accordance with the international standard (ISO 10303). In addition, with the extrinsic impacts generated by the energy consumed during the building operation, it provides a comprehensive evaluation of the environmental impacts generated by a building during its life span. An application example is the comparison of the environmental impacts generated by different variants of the same project, which may differ in terms of constructive solutions, such as insulation thickness, use of low-emissivity glazing system or the supply of electricity with photovoltaics panels. The aim is to quantify the global environmental contribution of the solution used to minimise its influence on the environment.

At multiple-view level, the proposed integrated approach greatly eases the holistic assessment of a project. The integrated application provides a rapid solution for the analysis of the global effect of the material variants used within a construction. For instance, it simplifies the evaluation of the performance modification obtained by covering a concrete ceiling with an acoustic absorbent material, which may concurrently affect the thermal inertia, the room acoustics and the lighting performance, and the environmental impacts.

More generally, the developments undertaken in this work enable the assessment of building performance, occupant comfort and environmental impact assessment. They enable a detailed analysis of the multiple-view performance of a project and provide a performance identity card in the form of an integrated performance view (IPV). The author will use this approach in the immediate future to analyse different typologies of existing office buildings.

8.2 POSSIBLE ENHANCEMENTS

The possible forthcoming improvements are:

- The room acoustics and photo-colourimetry database provides a limited number of absorption coefficients sets. It could be completed to supply a more representative range of materials and construction systems. The case study analysis has shown that some data required to perform the intrinsic LCIA are rare or unavailable. For the material fabrication and the transport phases, the impacts are available for most of the building materials. This is not the case for material attributes such as the loss rate or the covered distance, which lead to a lack of data confidence. To provide a complete environmental database that obtains scientific recognition, more information must be gathered.

- The model proposed in this work for the assessment of the environmental impact contribution of the assembly and deconstruction phases can be improved. Currently, the impact factors used for the calculation are expressed for a single functional unit. To provide a flexible storage and use of data, it may be convenient to differentiate the impacts factors with different functional units.

- The analytical equations used to assess the reverberation time are able to handle a large variety of spaces but are not appropriate for elaborated spaces such as large concert halls and operas. Implementation of advanced simulation methods, such as ray tracing, to improve the assessment of the reverberation time of complex spaces is required. In addition, such methods will give access to other indicators that can provide complementary information on the room acoustics performance of the analysed space and support virtual audio reconstruction (auralisation).

Finally, the developments undertaken in this work can be regarded as the foundation for the development of an integrated application towards a holistic assessment of building performance that may include additional views such as cost estimation or construction planning.

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ABBREVIATIONS

AEC	Architecture, Engineering and Construction
AP	Acidification Potential
BCF	Building Construction File
BDM	Building Data Model
BEPAC	Building Environmental Performance Assessment Criteria
BREEAM	Building Research Establishment Environmental Assessment Method
BSP	Building Simulation Program
CAD	Computer Aided Drawing
CAL	Computer Aided Learning
CEN	European Committee for Standardisation
CIBSE	Chartered Institution of Building Services Engineers
CML	The Centre of Environmental Science, Leiden University
DBMS	Database management system
DF	Daylight Factor
DXF	Drawing eXchange Format
EI	Environmental impacts
EOS	Energie Ouest Suisse
ESP-r	Environmental Systems Performance, r stands for 'research' version
FU	Functional Unit
GUI	Graphical User Interface
GWP	Global Worming Potential
IAI	International Alliance for Interoperability
IAQ	Indoor Air Quality
IF	Impact factor
IFC	Industry Foundation Classes
IGES	International Graphics Exchange Standard
IPV	Integrated Performance View
ISO	International Organisation for Standardisation
IT	Information Technology
LCA	Life Cycle Assessment
LCIA	Life cycle impact assessment
NIAM	Nijssen Information Analysis Method
NRE	Non Renewable Energy
O-O	Object-Oriented

OS	Operating System
PDM	Product Data Model
PM	Project Manager
POCP	Photochemical Ozone Creation Potential
PPD	Predicted Percentage of Dissatisfied
SIA	Swiss Society of Engineers and Architects, Switzerland
STEP	STandard for Exchange of Product Data
UCPTE	Union for the Co-ordination of Transmission of Electricity
UoD	Universe of Discourse
USL	Union Suisse pour la Lumière
VCP	Visual Comfort Probability (Guth)
VDU	Visual Display Unit

APPENDIX A

EXAMPLES OF HOLISM

This appendix gives some examples of combined effects related to various domains of building physics. These effects are antinomic (👎) when the solution or system illustrated in the example implies an advantage in a particular domain but a disadvantage in another domain. On the other hand, the effects converge (👍), when they improve the situation. The views listed in Table A.1 have been taken two by two in this appendix and illustrated with examples located in the indicated paragraphs. These examples are not exhaustive and many other examples exist.

vs	Environment	Acoustics	Lighting	Ventilation	Energy/thermal
Energy/thermal	A.1	A.2	A.3	A.4	A.5
Ventilation	A.6	A.7	A.8	A.9	
Lighting	A.10	A.11	A.12		
Acoustic	A.13	A.14			
Environment	A.15				

Table A.1 Paragraph numeration corresponding to the multiple-view examples.

A.1 Energy/Thermal vs Environment

👍 A double insulated glazing system using two panes of 6 mm clear float glass with a 12 mm air gap (6/12/6) has a central U-value of about 2.9 [W/m² K]. To reduce the U-value, a low emissivity (low-e) coating can be deposited on the external face of the internal pane. In the case of a soft, low-e coating, the central U-value decreases to around 1.5 [W/m² K].
Comparing both types of glazing with respect to environmental impacts generated during the manufacturing phase, the only difference in the fabrication process is the low-e coating deposit. Thus, the low-e glazing system has a more adverse environmental impact than the glazing without the coating.
If the assessment includes the energy consumption related to the glazing system, the low-e variant induces a reduction of energy consumption due to its lower U-value, which is significant enough to offset the unfavourable environmental impacts related to the coated pane.

- The indoor air temperature has a considerable impact on the thermal comfort of the occupants. The raising of that temperature increases the energy consumption, which has a direct influence on the natural energy resources. It also has a baneful impact on the environment as it increases the quantity of emitted pollutants.

A.2 Energy/Thermal vs Acoustics

- To reduce heat transfer through a glazing system, an inert gas, such as argon (Ar), can be used as it has a lower conductivity than air. Since it is also less dense, the use of argon (but also krypton) increases at the same time the airborne sound reduction index (R'w) to about 2 [dB] depending on the spacer thickness.

- To reduce the overheating risk in a non-cooled building, it can be an advantage to have a good thermal inertia provided by materials with a good thermal effusivity. Unfortunately, these materials, which are rather dense and hard, do not absorb much sound. So to provide an acceptable reverberation time in accordance with the room function, part of the internal surface(s) might be covered with sound absorbent materials (false ceiling, carpet, etc.). As these acoustic materials have generally a weak effusivity, the thermal inertia of the room is reduced again.

A.3 Energy/Thermal vs Lighting

- Compared to other shading devices, movable external louvers are very efficient in reducing solar heat gains. They are also very suitable for the control of glare sources during sunny days. Adjusting the slates orientation allows protection from direct solar radiation. Thus, external blinds can simultaneously control solar heat gains and visual comfort.

- Body tinted glass is a means to reduce solar heat gains. However, this type of glass has a low colour rendering index (Ra < 95), which can lead the occupants to compensate the weak colour rendering on the working plane by using artificial lighting, even if the room illuminance is acceptable for the activity in progress. This use of artificial light increases the internal gains that need to be evacuated.

A.4 Energy/Thermal vs Ventilation

- In a naturally ventilated building with sufficient thermal inertia, the passive night cooling strategy (evacuating the thermal loads accumulated during daytime with the help of night time natural ventilation) simultaneously improves the thermal comfort and the indoor air quality (IAQ).
  An other example: the extracting air vent of a mechanical ventilation can be combined with the luminaries in order to evacuate the internal gains due to light at the nearest of the source location. This solution is not adapted to an indoor environment with dust, which could form a deposit film on the luminary and therefore reduce the lighting efficiency.

- For an acceptable IAQ, a sufficient air change rate has to be provided, which can be achieved in a naturally ventilated building with an adequate openings management. If the openings are open when the ambient air temperature is higher than that in the room, the heat gains that need to be evacuated increase, which can lead to an overheating problem, such as in the case of a classroom with low thermal inertia.

A.5 Energy/Thermal vs Energy/Thermal

Compared to normal glazing (clear float), low emissivity (low-e) coated glazing has a lower U-value, which reduces the energy demand. At the same time the low-e coating increases the pane temperature, which improves the thermal comfort.

Selective solar control coatings reduce the solar transmittance of glazing and thus reduce the solar gains. During the warm period, the reduction of the solar gains can improve the thermal comfort in a non-cooled building or reduce the cooling demand in a cooled building. In fact, solar control coating reduces solar gains throughout the year, even in wintertime. During the cold period, this reduction in solar gains can lead to an increase in the heating demand. In this case the solar control coating has an antinomic energy impact depending on the period of the year.

A.6 Ventilation vs Environment

In some cases, natural ventilation can provide an acceptable Indoor air quality (IAQ) without the help of any mechanical system. In those cases, there are no environmental impacts related to the construction materials and the energy necessary to operate the mechanical equipment.

In a polluted environment, mechanical ventilation can be the most appropriate means to achieve an acceptable IAQ. But the materials and energy necessary for that equipment increases the environmental load of the building.

A.7 Ventilation vs Acoustics

The frame joint is a window component that is sensitive to infiltration and external airborne insulation. In a noisy and polluted environment, it might be preferable to seal the joint and to supply fresh air by means of mechanical ventilation equipped with filters.

For the purposes of natural ventilation, the windows might be kept open. In the case of a noisy external environment, the sound pressure level (SPL) inside a room will rise as soon as the window is open. Depending on the external SPL and the function of the room, the internal SPL can exceed the maximum admissible limit. A typical example is a classroom near a heavy traffic road.

A.8 Ventilation vs Lighting

A solar chimney is used to improve the daylight availability. It might also improve the natural ventilation draught by raising the neutral level. By correctly designing the upper aperture (movable, rain, etc.) and using appropriate reflecting material, the system can be directly connected to a room.
An other example: When the window is opened to provide natural ventilation, it also increases the daylight factor (less impact due to the frame and the transmittance of the glazing).

A vertical roller blind can be used to control solar gains and/or glare sources. Unfortunately, when the blind is lowered to protect from the glare sources, it is an obstruction to the airflow, which reduces the air change rate and thus may lead to a reduction of the IAQ. The system can be improved by using an awning or retractable vertical louvers.

A.9 Ventilation vs Ventilation

The author will be pleased if you have an example to submit to him. Thank you in advance for any suggestion.

Opening a window might improve the IAQ (odours, humidity, etc.). This solution is conceivable as long as the air entering the building does not exceed a maximum admissible concentration of a particular pollutant. Otherwise, the entering air will increase the concentration of the incriminated pollutant in the room. Depending on the quality of the external air, natural ventilation can be inappropriate and has to be replaced with a mechanical ventilation that includes the filtering of the incoming air. Furthermore, during the heating period, the opening of a window increases the heat loss due to ventilation.

A.10 Lighting vs Environment

Increasing the daylighting autonomy reduces the use of artificial lighting, which leads to a reduction in electricity consumption. This energy reduction has a direct effect on the energy resources. To be completely objective, the environmental impact should be compared for daylighting and artificial lighting for the same functional unit and include the whole life-cycle phases of the various materials and processes used in both cases.

The use of artificial lighting has a direct influence on the energy resources and the emitted pollutants due to the electricity consumption and the luminary materials.

A.11 Lighting vs Acoustics

The annual daylight sufficiency is the percentage of time during which the daylight illuminance is enough for a particular task and depends among other parameters on the reflection coefficient of the material used. The higher they are, the higher the internal reflected component of daylight is. Thus, the use of a bright material with a medium or high light reflection coefficient increases the annual daylight sufficiency. Acoustic false ceilings are generally of a bright colour, which increases their light reflection factor.
It should be noticed, that if an absorbent (porous) material with high acoustic absorption coefficients at high frequencies has not the desired colour, do not change its surface appearance by applying a surfacing (paint, finishing, or wallpaper). It will reduce its absorption capacity at these frequencies.

To guarantee an acceptable illuminance in a room, it is recommended to size the glazing area so that enough daylight is available on the work plane. The larger the glazing area, the more daylight is available. But from the point of view of room acoustics, glass is a rather low absorbing material compared to fitted carpet or to a false ceiling. If the glazing area is large, the necessary acoustic absorption (equivalent area) needs to be provided by the remaining surfaces of the room, especially for high frequencies. Furthermore, the airborne sound reduction index (R'w) of a glazing is generally lower than the R'w of the opaque part of the facade. Increasing the glazing area reduces the airborne sound insulation of the facade

A.12 Lighting vs Lighting

👍 A light redirecting system, such as a light shelf, increases the daylight factor in the back of a room and at the same time homogenises the illuminance distribution in the room and provides fixed eaves (the external collector), which might reduce the glare sources when placed on a South facade.

👎 The higher the window fraction is, the more daylight is available. But at the same time it increases the risk of glare sources.

A.13 Acoustics vs Environment

👍 Acoustic nuisance is a source of neighbourhood conflicts. By improving the acoustic insulation and reducing the environmental noise, it is possible to increase the soil use (densification of urban area), which reduces the environmental impacts of human development.

👎 The acoustic «mass law» induces that increasing a material mass reduces the airborne sound transmission through the material. The thicker the layer is, the higher the reduction index (R'w) of a material (except at the resonance frequency).
On the other hand, the increase of the layer thickness increases the material mass and thus increases its environmental impacts.

A.14 Acoustics vs Acoustic

👍 It is possible to improve the acoustic insulation and absorption coefficients of an element composed of a support (concrete, brick, etc), a mineral insulation, and a wooden board, by keeping an air gap between the insulation material and the support.

👎 An open window definitely has a higher acoustic absorption coefficient than the same window but closed. But from the view of airborne acoustic insulation, the closed window is generally preferable.

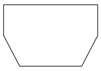
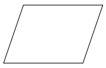
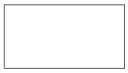
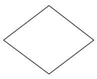
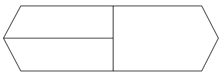
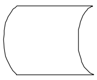
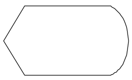
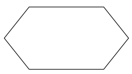
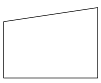
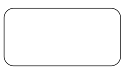
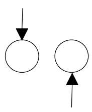
A.15 Environment vs Environment

👍 The maintenance of a forest is necessary to keep the bio-diversity of animals and plants. In an balanced environment, it requires the elimination of a plant mass that equals the quantity regenerated by the forest. In Switzerland this equilibrium is not yet achieved and the mass of cut down trees could be increased and used for instance in wood fibre insulation.

👎 In the past, polystyrene was manufactured using HCFC gas, which had the advantage of reducing the conductivity of the material. Due to environmental awareness, this gas was forbidden and is currently replaced with air, which has reduced the environmental impacts related to the material manufacturing process. This composition modification of polystyrene has slightly increased its conductivity, which implies a slight increase of the energy consumption.

APPENDIX B

FLOWCHARTS SYMBOLISM

	Beginning or End of the flowchart
	View (domain)
	Input or Output operation
	Computation process
	Decision. A choice is made between two alternatives
	Iteration loop
	Transaction file
	Display information
	Computer model
	Manual input
	Application
	Direction of program flow
	Flow chart connector

APPENDIX C

DATA EXCHANGE FORMATS

C.1 Native Format

Native mode corresponds to the transfer of data from one application to another without an intermediate translation. An application that uses, saves and reads only its native format requires from other applications to export the same format, whatever the data models used by the other applications. In other words, these must be able to generate a data model that has the native format of the receiving application. To allow *n* systems to be able to exchange (import and export) data, *n(n-1)* translators are necessary.
This is the most efficient method of transfer, since no data is lost and no errors are likely to occur during transfer, but it requires full transparency of the native format.

C.2 Neutral file format

Neutral file format is a standardised representation of the information, which can be used by different applications. Each application needs two pre-processors to exchange the data information, one to read and one to write the neutral file. In that case *2n* pre-processors are necessary to allow *n* systems to communicate. The neutral file format has the advantage, compared to the native mode, that with more than three applications involved, it requires fewer translator utilities. Various neutral formats are currently available on the market. Some of the most common formats are summarised below.

> **International Graphics Exchange Standard** (IGES), proposed by the US National Bureau of Standards (NBS) in 1980, has become an AINSI standard format for CAD data in 1981. The format is supported by all important CAD applications, however, it is an older standard that understands wireframe and surface geometry but has very limited support for solid geometry. While this is a limitation within IGES, most solid modellers can take IGES surface data and re-create the solid from it, and almost every CAD system supports IGES exchange. More details can be found in [IGES1991] or [Vou1996].
>
> **Data eXchange Format** (DXF) is the native format of the AutoCAD program developed by Autodesk and has become a defacto standard for the exchange of 2D/3D geometry. All CAD applications accept this format and are able to convert to and from its native format. Recent additions to the DXF standard allow the support of wireframe, surface and solid representation. More details can be found in [Aut1992].

These two standards are not based on information modelling methods and there is no clear distinction between logical, application and physical specification .Since their development, awareness of the utility of multiple-view and the volume and complexity of the information has increased, and therefore the need for a common format that enables the exchange of data between the different applications has arisen. Clearly, an automated design analysis requires a standard model that provides more information than the geometry.

To improve the building representation, international organisms channel their effort into developing and promoting the following two neutral file formats.

Standard for Exchange of Product data model (STEP) is an international exchange standard developed by the International Organisation for Standardisation in ISO 10303 [ISO1989] for representing and exchanging product data information. The modular structure of STEP, whose development started in 1984, has the ambition to cover all aspects of a product (geometry, topology, tolerance, materials, etc.) for all industry domains and is not limited to AEC (Architecture, Engineering and Construction). It includes the specification of an object-like formal language (Express) for the description of the representation of the data. The current developments are performed under the control of ISO, Technical Committee 184 (TC184, Industrial Automation Systems), Subcommittee 4 (SC4, Industrial Data and Global Manufacturing Programming Language). More details can be found in [Bou1995; ISO1994a; Owe1997].

International Foundation Classes (IFC) is a recent data format developed by the International Alliance for Interoperability (IAI) to provide a new standard data model. The IAI aims to provide standard definitions of attributes associated to AEC entities only, the structure and relationship between these entities, and a standard format for sharing the information. More details can be found in [Baz1997; Tol1999].

Further information on other data exchange formats such as VDAIS, VDAFS, SET can be found in [Vou1996]

APPENDIX D

BUILDING SIMULATION PROGRAMS

The table on the next page lists information regarding the simulation programs mentioned in this document. The Web site address listed in the table may evolve with time. If so, the simulation tool home page might be found with a search engine using the application name as key word.

Name	Origin	Reference	Web site
ADELINE	International Energy Agency (IEA)	[Erh1997]	http://www.radsite.lbl.gov/adeline/HOME.html
BUS++ (BUilding Simulation tool coded by C++)	VTT Building Technology, Finland	[Tuo1997]	/
Bsim2000 (successor to Tsbi3)	By og Byg, Horsholm, Denmark	[Gra1999]	www.by-og-byg.dk/english/publishing/software/bsim2000
COMBINE (COmputer Models for the Building INdustry in Europe)	EU Commission's Directorate General XII	[Aug1994]	http://erg.ucd.ie/combine.html
BDA (Building Design Advisor)	Lawrence Berkeley National Laboratory, USA	[Pap1997]	http://kmp.lbl.gov/BDA/
EcoPro	Institut für Industrielle Bauproduktion (IFIB), Germany	[Koh1997]	http://www.ifib.uni-karlsruhe.de
Eco-Quantum (SimPro)	Dutch governement	[Mak1997]	http://www.ivambv.uva.nl/uk/producten/product7.htm
EnergyPlus (DOE-2 and BLAST	U.S Department of Energy (DOE), USA	[Hua1999]	http://www.eren.doe.gov/buildings/energy_tools/energyplus/
EQUER / COMFIE	Ecole des mines de Paris, France	[Peu1999]	http://www-cenerg.ensmp.fr/english/themes/index.html
ESP-r (Environmental Systems Performance; r for "research")	Energy System Research Unit, UK	[Cla1997]	http://www.esru.strath.ac.uk/ESP-r.htm
Radiance	Lawrence Berkeley National Laboratory, USA + Solar Energy and Building Physics Lab. CH	[Lar1998]	http://radsite.lbl.gov/radiance/HOME.html
RIUSKA	Olof Granlund Oy, Finlande	[Wri1997]	http://www.granlund.fi/English/tyo-riuska.htm
UO (Dutch abbreviation of Uniform Environment)	Association for Computerisation in the Building and Installation Technology, The Netherlands	[Plo1997]	http://www.vabi.nl/uo/uoe.htm
TAS (Thermal Analysis Software)	Environmental Design Solutions Limited (EDSL), UK	See web site	http://ourworld.compuserve.com/homepages/edsl/
TRNSYS (Transient Systems Simulation Program)	Solar Energy Lab (SEL) at Uni. of Wisconsin-Madison, USA	[Bec1994]	http://sel.me.wisc.edu/TRNSYS/Default.htm

Table 8.1 Information on the simulation applications mentioned in this document.

APPENDIX E

LIFE CYCLE DECOMPOSITION

This appendix reports the life cycle phase decomposition used in the data model. The life cycle of a product (material or service) covers a wide range of phases from the material manufacturing to the material elimination after the decommissioning of the building. The following table summarises the life cycle phase decomposition extracted from the literature with the corresponding references. This list is not exhaustive, but summarises the phases that are commonly used to describe the life cycle of a building material.

<table>
<tr><th>Material life cycle stages</th><th>Introduction to LCA [Goe1997]</th><th>Pre-fabricated element [Hel1996]</th><th>Material Transport [Mil1998]</th><th>Building LCIA [Kod1997]</th><th>Insulation LCA [Erl1997]</th><th>Ecological eval. of paints [FOEFL1994]</th><th>LCA methodology [OFE1991]</th><th>In this work</th></tr>
<tr><td>• Raw material extraction</td><td rowspan="4">✓</td><td rowspan="4">✓</td><td rowspan="4">✓</td><td rowspan="4">✓</td><td>✓</td><td>✓</td><td>✓</td><td rowspan="4">✓</td></tr>
<tr><td>• Raw material processing</td><td>✓</td><td>✓</td><td>✓</td></tr>
<tr><td>• Raw material transport</td><td>✓</td><td>✓</td><td>✓</td></tr>
<tr><td>• Material manufacturing</td><td>✓</td><td>✓</td><td>✓</td></tr>
<tr><td>• Transport to construction site</td><td></td><td>✓</td><td>✓</td><td></td><td></td><td></td><td>✓</td><td>✓</td></tr>
<tr><td>• Construction assembly</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td></td><td>✓</td><td></td><td>✓</td></tr>
<tr><td>• Transport to building site
(prefabricated element)</td><td></td><td>✓</td><td></td><td></td><td></td><td></td><td></td><td>✓</td></tr>
<tr><td>• Placement on building
(prefabricated element)</td><td></td><td>✓</td><td></td><td>✓</td><td></td><td></td><td></td><td>✓</td></tr>
<tr><td>• Building operation (utilisation)</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td></td><td>✓</td><td>✓</td></tr>
<tr><td>• Maintenance</td><td></td><td>✓</td><td>✓</td><td></td><td></td><td>✓</td><td></td><td>✓</td></tr>
<tr><td>• Replacement</td><td></td><td></td><td></td><td>✓</td><td></td><td></td><td></td><td>✓</td></tr>
<tr><td>• Deconstruction</td><td></td><td>✓</td><td>✓</td><td>✓</td><td></td><td></td><td></td><td>✓</td></tr>
<tr><td>• Transport to waste management site</td><td></td><td>✓</td><td>✓</td><td></td><td></td><td></td><td>✓</td><td>✓</td></tr>
<tr><td>• Waste management</td><td>✓</td><td>✓</td><td>✓</td><td></td><td></td><td>✓</td><td>✓</td><td>✓</td></tr>
</table>

Table E.1 Examples of life cycle decomposition.

Further life cycle decomposition examples that fit this decomposition can be found in [Ada1996; Bai1994; Eye2000; Håk1998; Imp1998; Lip1998; Mil1998; Peu1998; Wei1996].

E.1 Material manufacturing phase

The system limits for the material manufacturing process encompass all the mass and energy flows downstream of the material to be used as a construction material. For a non-converted material, they take into account only the material extraction. For a construction material composed of several raw materials, the system limits include the raw materials extraction, their possible transport to the manufacturing site and finally their pre-processing.
As already stated in the LCIA chapter, the environmental impacts generated by raw material extraction, transport and processing are merged into the manufacturing phase because of the rare availability and the volatility of such information.
The manufacturing phase is related to the material and thus the corresponding information is stored at the material level.

E.2 Transport from manufactory site to construction site

This phase represents the transport of the materials from the manufacturing site were they have been processed to the construction site were they will be assembled. For a prefabricated construction, such as a window, the construction site corresponds to the factory, were the materials, such as the panes, the frame or the spacer, are assembled. For materials that do not belong to a prefabricated element, the construction site is equivalent to the building site. This is the case for most of the construction material.
It may happen that a material, such as concrete, can be used either in a prefabricated element or directly on the building site. In such cases, properties, such as the cost or the environmental impacts, are different according to the processing. To differentiate the material as a function of its use, it is necessary to store two different concrete types. Because of the relational approach used to manage the information stored in the database, it is possible to distinguish between the two uses of a same material with a flexible and efficient management of the material properties.
Even if the materials are transported to the same site, they do not necessarily come from the same manufacturing site. Therefore, the transport to construction site phase is material related.

E.3 Construction assembly

The construction assembly phase takes place at the construction site (not necessary the building site) and corresponds to the process during which the materials are assemble on the construction site. It may include several processes between the delivery of the materials at the construction site and the moment the construction is fully assembled. For instance, the construction assembly phase of a window involves more than one process, i.e. the process required to assemble the transparent unit and the process to assemble the frame and the transparent unit.

E.4 Transport from construction site to building site

This phase corresponds to the transport of an element from the construction site to the building site. According to the definition of the construction site, this transport exists only for prefabricated element. This phase is not relevant for materials that are erected directly on the building site. For a prefabricated building element, such as a window, transportation should include the transport of the constituent materials from the manufacturing site to the prefabrication site and the transportation from the prefabrication site to the building site. This second transportation is applied to all constituents of the prefabricated element and therefore the journey distance and the means of transport might be considered equal for the whole element. Thus, all its constituent materials are transported at the same time by the same means of transport over the same distance and therefore this transport phase is related to the whole element. As in any other transport phase, it may happen that the journey is effectuated with different means of transport, each means covering a different distance.

E.5 Placement on building (prefabricated element)

In the placement on building phase, a prefabricated element, such as a window, is integrated into the building. This phase should not be mixed-up with the «construction assembly» phase, which describes the assembly of non-prefabricated elements at the building site. For instance, the shell construction is erected on the building site and therefore does not need to be placed on the building. For a non-prefabricated construction, this phase is therefore not relevant.

E.6 Building operation

The utilisation phase corresponds to the period of the building life during which the building is operational and has to provide an acceptable indoor environment quality. The building quality is determined to a large extent by the choices made during the design phase in terms of concept and materials, which have a direct impact on the building performance.
During the utilisation phase, generated cost is not directly related to the construction materials, but to the energy consumed by the building services.

E.7 Maintenance

An element may be maintained periodically during its life span so that it keeps its physical properties (washing the window glass), to preserve its primary aesthetic aspect (painting a surface) or for the occupants' health quality (using a vacuum cleaner). The maintenance is related to the whole element and therefore the corresponding information is stored at the construction level.

E.8 Replacement

The replacement takes place at the end of the element's service life. The service life (or material life time) is the period of time after the installation during which all essential properties of the material still fulfil the initial requirement, when periodically maintained. At the end of its service life, the material has to be replaced.

E.9 Deconstruction phase

At the end of the building life, the deconstruction phase covers the processes necessary to deconstruct the building. The construction may be separated into its constitutive materials, which are then stocked in specific containers. Containers stock materials of the same kind, independently of their former location on the building, with regard to their final disposal management. All the materials are finally evacuated to the same disposal site. The deconstruction process is related to the material and the corresponding information is stored at the material level.

E.10 Transport to waste management site

After the deconstruction phase, the building materials are transported to the final processing site, according to the category of the materials. The transported mass encompasses all the construction materials required during the building life, including supplementary material necessitated to compensate loss or breakage during the transport and assembly phases, and the replacement materials. As in any other transport phase, it may happen that the journey is effectuated with different means of transport, each means covering a different distance.

E.11 Waste management

The waste management phase corresponds to the final process applied to a material at the end of its life. According to several sources, waste management can be grouped into three final categories:

- Recovering, which includes recycling and reuse of materials
- Incineration
- Storage in a landfill

However, some materials may have more than one disposal channel. For instance, a certain percentage of concrete waste may be recycled and the remainder put into storage in a landfill. Furthermore, the transportation from the building site to the waste management site may differ depending on the elimination process. As different waste management channels generate different environmental impacts, it is important to allow the possibility for a material to have different elimination channels. The retained solution enables for each material to have a specific elimination rate for each of the three previously described final elimination categories. And for each existing category, there is a possibility to account up to three different means of transport.

No claim to completeness in terms of life cycle stages is made for this description. But it could easily be extended to other phases and proposes the backbone of a problem-driven solution for the development of an integrated approach, which supports life cycle assessment.

APPENDIX F

ESP-R SHORT USER GUIDE

Although expert users may use ESP-r at the design stage, this simulation tool should be considered as an analysis program that requires advanced knowledge in building simulation. This appendix briefly summarises the main features requested by ESP-r to perform a simulation.

F.1 Building model description

Geometry model

In order to perform a simulation with ESP-r, the first step consists in creating the 3D geometry model of the project to analyse, based on thermal zones. A thermal zone is a volume of air assumed to have homogeneous thermodynamic properties. A zone is used to represent a room, a portion of a room or a concatenation of several rooms. The geometric description of a zone is composed of an air volume, which is bounded by closed polygons that follow certain conventions. Each surface is made up of a list of vertices (specified at the zone level), ordered anticlockwise when facing the `outside' face of the surface.

A surface is a polygon with associated attributes such as orientation and a specific multilayer construction. The description of the layers of the construction is defined from the outside to the inside. If the surface is a partition composed of a non-symmetrical composite construction, the user will need to define two composites, with one defined in reverse order to the other. Surfaces have two sides, one facing the zone (inside) and the other connected to a boundary condition (another zone, ground, outdoors, etc.). A surface may be opaque or transparent.

Construction model

The materialisation of a construction requires the definition of its constituting materials and the corresponding thickness. The definition and description of the thermophysical properties is based on data stored in two databases:

1) *A Material Data Base*, which holds physical properties such as the density, specific heat, conductivity, diffusion resistance, surface absorption and emissivity of elements such as earth, stone, steel, oak etc. This database is normally in a binary format for quick random access, although an ASCII form is available for transfers between different machine types.

2) A *Multilayer construction Database*, which defines the composition of constructions such as walls and glazing systems in terms of layers of materials of particular thickness in a particular order and, where appropriate, with a named set of optical properties. Items in this database are accessed through their construction name and therefore it is necessary that unique names are used.

Ventilation and infiltration
Ventilation and infiltration can be defined by profile schedules of air changes per hour for infiltration (from the outside) and ventilation (between zones). It also possible to perform a dynamic prediction of mass flow within a network of nodes and flow components acted upon by external pressure distribution, stack effects and buoyancy. In this mode the user describes the possible paths of air or water flow, components such as doors and openings where flow may pass and components such as fans, which may modify flow, and asks the system to predict the dynamic flow.

Internal gains
The internal gains can be defined by hourly profiles for occupants, lighting and equipment. It is also possible to differentiate between weekdays, Saturday and Sunday.

Shading analysis
The shading and insolation module provides facilities for calculating the temporal distribution of shading patterns on exterior surfaces and the distribution of insolation within zones.

Plant modeling
In the case where a project requires a detailed analysis of plant systems, the user has the possibility to undertake a simulation based on a network of components that can be linked to mass flow networks if required.

Controls
All control functions are defined by sensors which are located at, for example, an air node, surface, or node within a plant component; by actuators located at an air node, surface or plant component; by a schedule of operation, set points and control laws. The specification of control systems within the project manager is via a selection of lists of options and specification of values.

F.2 Simulation

The simulator (bps) takes descriptions of simulation problems generated by the project manager. The simulator will deal with problems that are related to buildings, plant systems and mass flow, separately or in combination. It also provides a tracing facility from which it is possible to extract simulation variables such as the flux at points within the problem and energy balance reporting. The simulator produces a results library, which may be explored via the results recovery module.

F.3 Performance assessment

The results analysis program (res) takes a simulation result library generated by the simulator and allows the user to explore the dynamic performance of a particular problem, by zone, via a range of graphic and tabular facilities. Included are time-variable graphs, variable-variable graphs, pie charts, 3-D surface plots of a variable over time, temperature profiles within constructions, and histograms.

Tabular facilities include causal energy balances and zone surfaces balance, energy balance reporting, time step listings for most temperatures and fluxes within a problem, interrogation of maximum and minimum values and comfort analysis. The results can be exported into a spreadsheet and presented in the form of an integrated performance view (IPV).

APPENDIX G

NIAM MODELLING LANGUAGE

Several languages, such as EXPRESS [ISO1994c] and UML (Unified Modelling Language) [Rum1999], have been developed to represent a conceptual schema of an information system. These conceptual languages are similar with minor differences in the overall expressive power and they share a set of commonly accepted concepts that are expressed in slightly different manners.

EXPRESS is an alphanumeric language, which can be processed by a computer, but as it looks too much as a computer code, it is hard for casual readers to understand the model. EXPRESS-G is a graphical version of EXPRESS that has been developed to ease the interpretation of the representation. Despite its standardisation, it may happen that the model development process is not well supported by the EXPRESS languages as pointed out by Tolman [Tol1992].

The conceptual language adopted in this document uses the Nijssen Information Analysis Method (NIAM) developed by Nijssen [Nij1989] since 1975. It is also known as Object-role modelling (ORM). NIAM relies on a graphical representation to support the conceptual representation of information, which offers several advantages: (1) it contains a high level of semantics and rules which yields more precision and less ambiguity; (2) it is a stable language, used by many academics and industries; (3) finally, NIAM can be manually or automatically translated into EXPRESS. The ISO uses the NIAM representation in parallel to EXPRESS [CEN1996c]

This appendix summarises the main definition and concepts that are necessary to understand the NIAM diagrams. It is made of a compilation of information extracted from various sources [Hal1995; Tur1990; Win1990].

G.1 Lexical and non-lexical objects

The description of NIAM, as that of any language, requires the definition of the vocabulary used.

Lexical object (label)	An object of a certain part of the real world or abstract world, which can be uttered, written down, or otherwise represented. Lexical objects always consist of letters, numbers, symbols and/or characters. Lexical objects can be used as names for or references to other objects. Lexical is derived from the concept of lexicon, which is a list of names of all objects that occur in a certain reality.

Non-lexical object (entity) An object in a certain reality (UoD), which cannot be uttered, written down, or otherwise represented. Non-lexical objects must be named by lexical objects or referred to by means of lexical objects.

To illustrate, the definitions and concepts defined below, the following example will be used:

«*Mary is a nurse employed at the Royal Maternity Hospital, Catherine is a nurse employed at the Central Hospital and Sophie is a nurse employed at both Hospitals*»

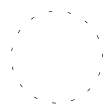
In this statement, *Mary, Catherine, Sophie*, *Royal Maternity* and *Central Maternity* are lexical objects. The three first names are lexical objects used as names to characterise a «*nurse»*. According to the definition, a nurse is therefore a non-lexical object. In other words, the first three lexical objects belong to the non-lexical object «*nurses*», while the latter two belong to the non-lexical object «*hospitals*».

The examples used below to illustrate the NIAM language are not directly connected to building simulation as it is useful to see a different example of the possibilities offered by the NIAM to represent abstract concepts. It is possible to replace a nurse's name with a physical attribute (ex. *density*) and the hospital entity with a physical domain (ex. *hygro-thermal*).

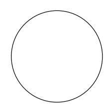
G.2 Lexical and non-lexical object type

The sets «nurses» and «hospitals» are non-lexical objects and belong to the same kind or type *nurse* or *hospital* respectively, which is described by the following terminology:

Lexical object type A set or class of equivalent lexical objects (label category), which is abbreviated LOT and represented with a dashed line circle



Non-lexical object type A set or class of equivalent non-lexical objects (entity category), which is abbreviated NOLOT and represented with a filled line circle



In the given example, the lexical objects *Mary, Catherine* and *Sophie* form a population of the LOT «First name», while the lexical object *Royal Maternity* and *Central Maternity* are lexical objects of the LOT «Hospital Name».
In the same statement, the nurses with the first name *Mary, Catherine* and *Sophie* form a population of the NOLOT «Nurse», while the hospitals with the name *Royal Maternity* and *Central Maternity* are elements of the NOLOT «Hospital». The representation of LOT and NOLOT is similar to the set theory, were objects are surrounded by ellipses.

G.3 Relationships

In the previous paragraphs, the basic vocabulary of the NIAM language has been defined. Now to complete the modelling language, grammatical rules are required to represent the relation between the vocabulary elements.

Fact An elementary statement that expresses a relationship between objects in a certain reality.

There are the following two kinds of facts:

Idea A fact that involves only non-lexical objects.

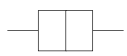
Bridge A fact that involves one lexical object and one non-lexical object. It indicates which lexical object represents certain characteristics of which non-lexical objects.

There are no facts that only concern lexical objects, because these kinds of facts can always be decomposed into the two previous kinds of facts.
The following elementary statements are *facts* extracted from the previous example:

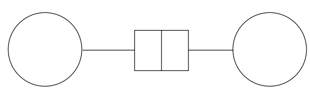
- *«Mary is the first name of a certain nurse»*, which is a bridge.
- *«Royal Maternity is the name of a Hospital»*, which is a bridge.
- «*Two nurses work for the same Hospital»* is equivalent to «*Mary and Sophie work for the Royal Maternity »*, which is an idea.
- *«Catherine is employed at the Central Maternity*», which is an idea.

Similarly to the lexical and non-lexical object type, the following types can be defined:

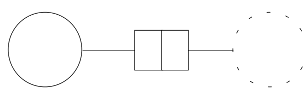
Fact type A set or class of facts that express the same kind of information.



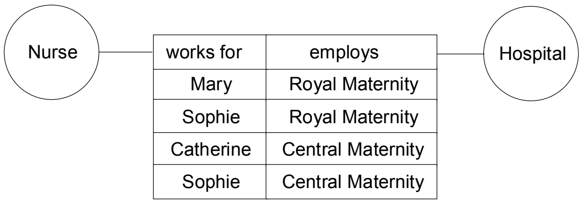
Idea type A fact type that exclusively involves NOLOTs and whose populations thus consist of ideas



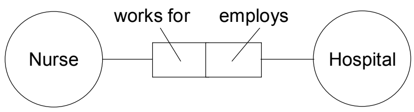
Bridge type A fact type that involves one LOT and one NOLOT and whose populations thus consist of bridges



From the previous example, it can be said that the statement «*Nurses work for Hospitals*» expresses the knowledge that there is a set or class of facts, which concern the NOLOT *nurse* and the NOLOT *Hospital*. These facts express the same kind of information, namely that a certain nurse works for a certain Hospital, and is named a fact type. It constitutes a schematic representation of the population diagram shown below.



Population diagram



Information structure diagram

G.4 Role and constraint

In the example given above *Sophie* works for more than one hospital. The role *works for* is in that case not unique. Some elementary statements can be restricted in terms of related objects, such as «*A nurse can work for only one Hospital at a time*».

According to the previous example, the following proposition can be made «*Mary and Sophie are nurses employed at the Royal Maternity Hospital, Catherine is a nurse employed at the Central Hospital*».

In the modified example, each nurse works for only one hospital, but one Hospital (*Royal Maternity*) can employ many nurses. In accordance with both representation diagrams, the following definition can be introduced.

Role Represents the relation between two objects (a column in a population diagram) symbolised with a rectangle

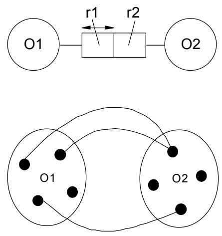
In the given example, *works for* is the role of the nurses within the hospital and *employs* is the role of the hospitals for the nurses.

Unique role A role in which every object of the object type of that role may only occur once in every population.

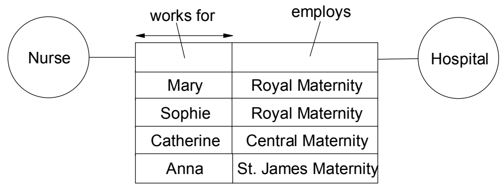
A unique role in the information structure diagram is characterised by an arrow over the top of the corresponding role. The following constraints are possible:

<table>
<tr><th>Definition and Representation</th><th>Example</th></tr>
<tr><td>

Uniqueness constraint on left role (*1:many* association). Role r1 of object O1 is unique.

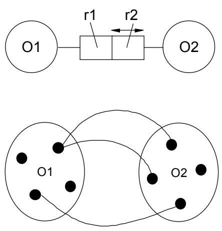


</td><td>

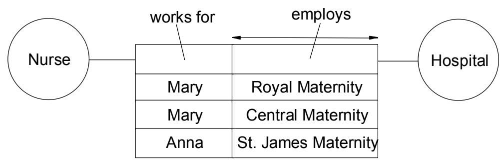


</td></tr>
<tr><td>

Uniqueness constraint on right role *(many:1* association). Role r2 of object O2 is unique.

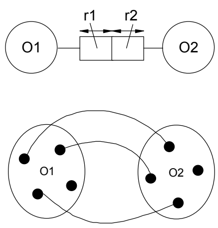


</td><td>

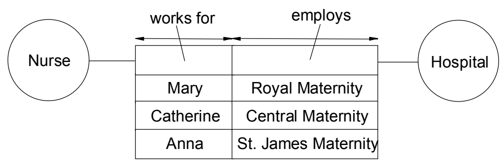


</td></tr>
<tr><td>

Uniqueness constraint on each role (*1:1* association). Role r1 of object O1 is unique and role r2 of object O2 is unique.

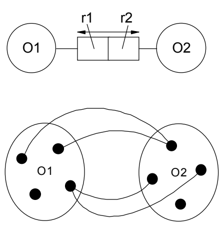


</td><td>

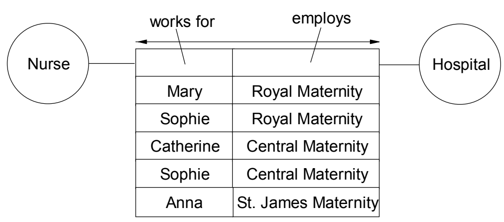


</td></tr>
<tr><td>

Uniqueness constraint on combination of roles (*many:many* association). The couple "role r1 of object O1" and "role r2 of object O2" is unique.



</td><td>

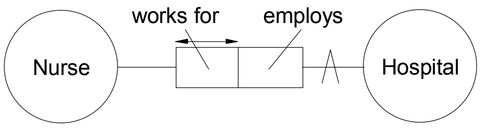


</td></tr>
</table>

In these four constraints, «many» does not mean «all». If every object of the object type must occur in the population of a role, then the total constraint has to be defined.

Total constraint A constraint that expresses the totality of a role or of a combination of roles.

The symbol $\wedge$ is used as an abbreviation of «All» and is placed between an object and its role as shown in the right part of the following example (all Hospitals employ (a) nurse(s)).



In this diagram of a total constraint, the role «Hospital *employs* nurse» is total while the role «nurse *works for* hospital» is not total. Not every nurse has to work for a hospital. Nurses may also work independently. Uniqueness and total constraint can be combined in the same information structure diagram.

APPENDIX H

RELATIONAL TERMINOLOGY

In a relational database management system (RDBS), the data are logically structured within relations. A **relation** can be seen as a table, in which a **tuple** corresponds to a row and an **attribute** to a column. The number of tuples is called the **cardinality** and the number of attributes the **degree** of the relation.

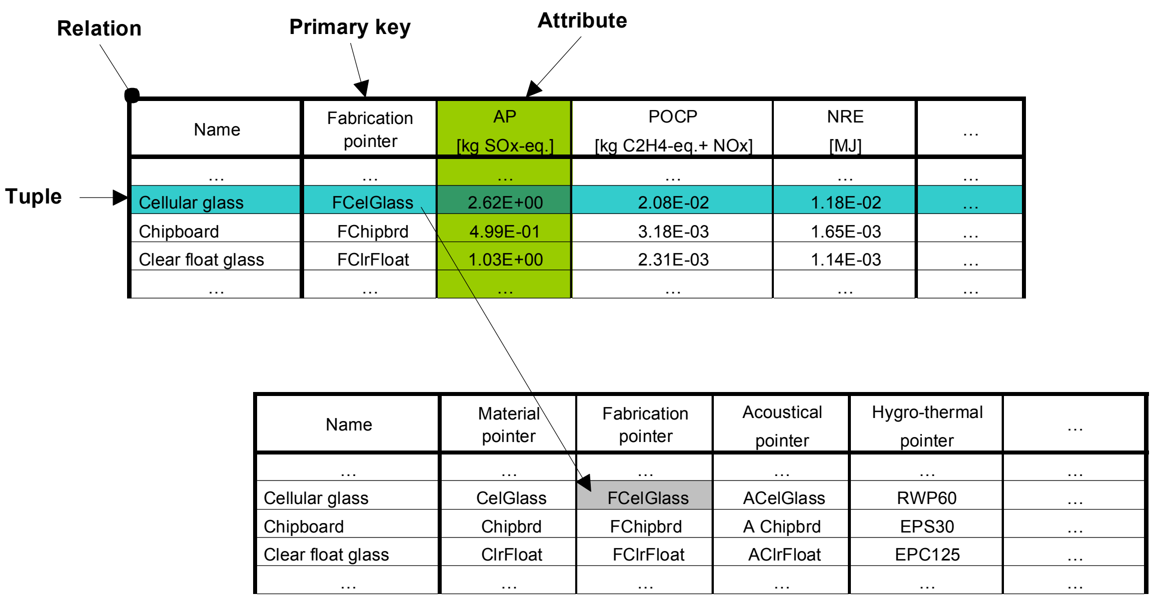


Figure H.1 Terminology of relational schema.

The **domain** of an attribute is the set of allowable values, i.e. a data type, such as an integer or a character. Finally, a **primary key** is defined as the selected attribute (or set of attributes) that is unique in a relation and can be distinguished from any other instance in the same relation. In the proposed model, the selected primary key has the entity pointer-name. That means, each name has to be unique in order to keep the consistency of the database. The primary key guarantees that the database has only one exact match in the relation. The different keys are then used as foreign keys in order to relate entities.

The Table H.1 summarises other terminology used in RDBS.

Formal	Database	Physical
Relation	Table	File
Tuple	Row	Record/Instance
Attribute	Column	Field

Table H.1 Alternative terminology for relational model.

Attribute integrity is important to keep a DBMS consistency. The integrity of the attribute values refers to the correctness of the stored data in the database, which is achieved by using constraints that are internal to the system. The database system enables data to be updated only if the constraints are not violated, otherwise it rejects the data. The constraints are recorded in the database core and will display a diagnostic message in response to an attempt to violate the constraint. In the database, there are the following levels of integrity constraints.

H.1 Attribute type constraints

An attribute constraint checks if an attribute value has the same attribute type as defined in the database, i.e. the correctness of the attribute domain. For instance, if the attribute type of a material lifetime is defined as INTEGER, the database should store only attribute values that are integer. This constraint category is part of the attribute definition (programming language) and therefore the compiler evaluates the type conformance automatically.

H.2 Attribute value constraints

The attribute value constraint defines the legal value of an attribute type. For instance, the material emissivity $\ni[0;1]$. The value constraint of an attribute is defined at the database level and is checked immediately during attribute value modification in order to avoid that an attribute acquires an inappropriate value.

H.3 Instance constraints

The instance constraints specify a constraint in terms of a particular instance. For example, in the disposal entity, the rates for recycling, dumping and incineration are stored. The instance constraint requires the sum of these three rates to be equal to unity.

APPENDIX I

BUILDING CONSTRUCTION FILE

This appendix gives an example of the different blocks that constitute the *building construction file* (BCF), which holds the constructions information.
The BCF header holds information at the project level, such as the configuration file name EOS.cfg) of the project, the building life time, and the number of materials and constructions listed in the BCF as shown in Figure I.1.

```
*Project_constructions
*Version, 1.19
*Date,Fri Dec 15 13:26:15 2000
*System,EOS.cfg
*Scope,thermal, lighting, ventilation, room acoustic, LCA
*Lifetime,  80.00
*Nb_mat,  21
*Nb_comp,  13
```

Figure I.1 Example of a BCF header.

The **layer-block** holds information at the material level, such as hygro-thermal data, the impact factors of the material manufacturing, the material transport to the construction site and the disposal management as shown in Figure I.2.

```
# material category, tag, name, description
*Material,Glass,CF4mm,4mm clear float,
*Domains,CF_Glass,SglGlazg,none,ClrFloat,none,
# Hygro-thermal details: tag, cond, dens, spec ht, emis abs etc.
*Hygro-Thermal,CF_Glass,1.05,2500.,720.,0.93,0.08,19900.,0.00,0.00,0.,0.,
# env effects: tag, nb trn (to construction site), life, break. during assembly, misc data, impacts
*Mat_effects,ClrFloat,1,30.00,0.070,0.0000,0.0000, 1.027E+00,2.310E-03,1.136E-03,1.440E+01,
# assembly transport: tag distance, breakage during transport, impacts
*Tran_assembly_site,Lorry28t,700.00,0.030,2.227E-01,1.913E-03,1.926E-03,3.731E+00,
# recycling: type, no transports, recycling impacts
*Dec_Recyc,RClear_float,1,0.850,0.000E+00,0.000E+00,0.000E+00,0.000E+00,
# recycling transport (building to recycling site): pointer, distance, rate, transport impacts
*Tran_Recyc,Lorry16t,160.00,3.713E-01,3.205E-03,3.307E-03,5.829E+00,
# incineration: type, no transports, inciner. impacts
*Dec_Incin, none,
# dump: type, no transports, dump impacts
*Dec_Dump,InertDp,1,0.150,5.570E-04,5.290E-06,5.760E-06,8.230E-03,
# dump transport (building to landfill site): distance, rate, transport impacts
*Tran_Dump,Lorry16t,100.00,3.713E-01,3.205E-03,3.307E-03,5.829E+00,
```

Figure I.2 Example of a layer block.

The **Construction bloc**k contains all information at the construction-level. It includes the optics, the colour and the acoustic absorption of the two construction sides, some environmental impacts and, finally, the list of the constituent materials as shown in Figure I.3.

```
# construction: index, tag, name, OPQ/TRN
*Gen_constr,  1,dbl_glz_int,dbl_glz_int,TRAN
*Optics,eos_int_win
# other & inside face colour detail: tag, red, green, blue, grey, type, pattern
*Colour_other,grey50,127,127,127,0.5,none,none
*Colour_inside,grey50,127,127,127,0.5,none,none
# other & inside face acoustic details: tag, type, unit, 17 coefs.
*Acou_other,Dgz4-12-4,C,unit,
0.220,0.200,0.180,0.170,0.150,0.130,0.120,0.100,0.080,0.070,0.050,0.040,0.040,0.030,0.030,0.020,0.020,
*Acou_inside,Dgz4-12-4,C,unit,
0.220,0.200,0.180,0.170,0.150,0.130,0.120,0.100,0.080,0.070,0.050,0.040,0.040,0.030,0.030,0.020,0.020,
# constructions assembly details: tag, nb of assembly impacts
*Constr_assembly,1,
s,PVCFrame,0.000,0.000E+00,0.000E+00,0.000E+00,8.534E-01,
*Tran_Constr,1,
Lorry16t,160.00,0.030,3.713E-01,3.205E-03,3.307E-03,5.829E+00,
*Assembly_at_site,none,
*Constr_maint,none,
#
# Layers: thermal layers, environ. layers
*Layers, 5, 5,
# layer T|S, mat category, mat tag, index, legacy index, thick
t,s,Glass,CF4mm,109,109,  0.00600,4mm clear float,
t,g,Gasses (for air gaps),Air,  1,  0,  0.06100,air (@ 25C),
t,s,Glass,CF4mm,109,109,  0.00600,4mm clear float,
n,c,Metal,Alu_spacer, 26, 25,  0.06000,Aluminium spacer,
n,f,Plastic and polymer,PVC_Frame,116,115,  1.0,PVC frame,
```

Figure I.3 Example of a construction block.

APPENDIX J

CML IMPACT ASSESSMENT METHOD

This appendix summarises the features of the CML methodology [Hei1992], which is used to perform the impact assessment. The CML approach, which is compatible with ISO 14040[ISO1997], includes a classification step and a characterisation step but no valuation of the effect scores is undertaken.

J.1 Classification step

Classification is the step in which the data from the inventory analysis are grouped together into a number of impact categories that represent different kinds of environmental damage. For instance, the CML classification knows the following fourteen environmental effect categories:

- Depletion of abiotic resources
- Depletion of biotic resources
- Enhancement of greenhouse effect
- Depletion of the ozone layer
- Human toxicity
- Ecotoxicity
- Photochemical oxidant formation
- Acidification
- Nutrification
- Waste heat
- Odour
- Noise
- Damage to ecosystems and landscapes
- Victims

J.2 Characterisation factors

In the characterisation step, the impacts obtained during the inventory analysis are aggregated within a given impact category, under the assumption that different pollutant substances do not have the same effect for a certain category. Each substance has a specific impact and therefore, the total effect score is equal to the weighted sum of all contribution. The weighting factors are named equivalency factor, classification factor or characterisation factor (CF) depending on the source.

The CF represents the relative impact of a substance compared to a reference substance. This reference substance depends on the analysed category. For the enhancement of the global warming potential, the reference gas is the carbon dioxide (CO_2). Thus, the multiplication of the CF by the pollutant load corresponds to an equivalent mass of CO_2 that will have the same effect on the global warming as the pollutant.
Several characterisation factors can be attributed to a pollutant, when it is implicated in different categories. For instance, NO_x contributes, among others, to acidification and photo-oxidant formation and thus has one factor for each category.

As an example, Table J.1 and Table J.2 list some of the characterisation factors of the global warming potential (GWP) and all factors of the acidification potential (AP) defined by the Intergovernmental Panel of Climate Change (IPCC) [IPCC1994].

Formula	Substance	GWP_{100} [kg CO_2-eq]
CO_2	Carbon dioxide †	1
CH_4	Methane †	24.5
CH_2Cl_2	Dichloromethane	15
$CHCl_3$	Trichloromethane (Chloroform)	25
N_2O	Dinitrogen oxide † (Laughing gas)	320
CH_2FCF_3	1,1,1,2-tetrafluoroethane † (HFC-134a)	1300
CHF_2Cl	Chlorodifluoromethane † (HCFC-22)	1700
CF_3Br	Bromotrifluoromethane † (Halon-1301)	5600
. . .	. . .	. . .

Note: The time horizon of 100 years has been retained for the GWP as it corresponds more or less to the life time of a building.

Table J.1 The CML characterisation factors of the global warming potential.

Formula	Substance	AP [kg SO_2-eq]
SO_2	Sulphur dioxide †	1.0
NO_2	Nitrogen dioxide	0.70
NO_x	Nitrogen oxides †	0.70
HCl	Hydrochloric acid †	0.88
NO	Nitrogen monoxide	1.07
HF	Hydrogen fluoride †	1.60
NH_3	Ammonia †	1.88

Table J.2 The CML characterisation factors of the acidification potential.

These characterisation factors correspond to the weighting factors used, for instance, in the CML method [Hei1992]. It may occur that the number of factors used for the calculation is limited to the elements that have effectively been inventoried. For instance, the characterisation factors with † are those used in the ESU'95 [Wei1995] database.

The characterisation factors are based on current scientific knowledge, which can vary as the insight into the physical phenomena and their effect on the environment progresses. Although the CF is defined on a scientific basis, there is not a general consensus for all categories. For the GWP and

POCP, the characterisation factors obtain a relatively high degree of international and scientific consensus, which is less the case for the AP [Gui1994].

J.3 Characterisation step

The characterisation consists in multiplying each load by its matching factor CF and summing up the results per impact category. For instance, during a process, the emitted gases implicated in global warming are aggregated by multiplying each inventoried emission with its specific CF and by summing up each contribution. The specific effect s_i of a pollutant substance i in an impact category j is then the product of the substance load and the characterisation factor CF that corresponds to the effect on this category. Finally the total effect S_j is the sum of the specific effect of the inventoried pollutant substances, i.e.

$$S_j = \sum_i s_i = \sum_i \left(CF_{ij} \cdot M_i \right) \tag{J.1}$$

where

S_j	Total effect in impact category j [Impact/FU]
CF_{ij}	Classification factor for substance i for the category j [mass of reference substance / mass of emitted substance i]
M_i	Load of inventoried substance i [mass of emitted substance/FU]

Note: the unit [Impact] is a generic representation of the unit related to the analysed impact. For instance for NRE, the impact unit is [MJ], while for the GWP it corresponds to [kg CO_2 -equiv.]

It may occur that the number of factors used for the calculation is limited to the elements that have effectively been inventoried. For instance, the characterisation factors in the previous tables with † are those used in the Weibel [Wei1995] database.

APPENDIX K

COMPOSITE MATERIAL

This appendix illustrates how a complex building element, such as a frame and a spacer, made of several materials, can be expressed as a *composite material*. The solution of replacing a complex component made of various materials (in shape and materials) requires a project external LCIA calculation of the considered components. The procedure described below concerns the manufacturing stage, for which the environmental impact of a composite *j* is given by:

$$IF_{composite,l}^{Manufacture} = \frac{\sum_{i \in j} \left(M_i \cdot IF_{i,l}^{Manufacture} \right)}{\sum_{i \in j} \left(M_i \right)} \tag{K.1}$$

where

$IF_{j,l}^{Manufacture}$	Impact factor *l* for the manufacturing of the composite material, in unit impact per mass [Impact/kg]
M_i	Mass of material *i*, in unit of mass [kg]
$IF_{i,l}^{Manufacture}$	Impact factor *l* for the manufacturing of the material *i*, in unit impact per mass [Impact/kg]

This approach is illustrated with the following two examples.

K.1 Example 1 : Frame

In the industry, the cross section of a frame is generally constant as long as the thickness of the transparent unit is below a certain value. For instance, Ego Kiefer, a major European frame manufacturer, has fixed this value to 36 mm [Ego1999]. Above that thickness, a second frame section is used. Thus, the linear mass of a frame can be considered as constant for a transparent unit that has a thickness below or equal to 36mm. The frame mass is then given by

$$M_{Frame} = {}^{lin}\overline{M}_{Frame} \cdot P_j$$

where

P_j	Element perimeter [m]
${}^{lin}\overline{M}_{Frame}$	Linear mass of the frame [kg/ml]

The calculation of the linear mass and the environmental impacts of the composite material requires a detailed segmentation of the frame components. Table K.1 lists the material manufacturing contribution of the materials constituting a PVC frame.

Raw Materials Manufacturing	Volume m3	Masse kg	NRE MJ	GWP kgCO2-equiv.	AP kgSOx-equiv.	POCP kgNOx-equiv.
Frame						
PVC	1.34E-02	1.88E+01	1.69E+02	7.37E+01	4.55E-01	7.25E-02
Aluminium 40% recycled	4.50E-04	1.22E+00	1.36E+02	8.29E+00	5.61E-02	3.61E-03
Steel	1.61E-03	1.26E+01	4.85E+02	2.81E+01	1.09E-01	9.10E-03
Total frame	1.55E-02	3.26E+01	7.90E+02	1.10E+02	6.20E-01	8.52E-02
Components						
EPDM	4.00E-04	4.00E-01	4.24E+01	1.29E+00	1.07E-02	6.18E-03
Aluminium (handle)	1.21E-04	3.27E-01	5.71E+01	3.48E+00	2.42E-02	1.56E-03
Steel (rails)	/	6.91E+00	2.65E+02	1.54E+01	5.97E-02	4.98E-03
Steel (hinges)	/	1.00E+00	3.83E+01	2.22E+00	8.64E-03	7.20E-04
Total compo.	5.21E-04	8.64E+00	4.03E+02	2.24E+01	1.03E-01	1.34E-02
Total	1.60E-02	4.13E+01	1.19E+03	1.33E+02	7.23E-01	9.86E-02
		Mean value[Impacts/kg]	**2.89E+01**	**3.21E+00**	**1.75E-02**	**2.39E-03**
		Mean value[Impacts/ml]	2.711E+02	3.012E+01	1.644E-01	2.241E-02
		Linear mass [kg/ml]	**9.38**	(per unit of frame lenght)		

Table K.1 Environmental effects generated during the manufacturing phase of the constituent materials of a PVC frame (frame length : 4.35 m).

The linear mass of the frame is stored as a special attribute in the physical data model. This pre-calculation must be repeated for each life cycle phase of the frame. The average impact factors of the frame materials' are stored in the database as a composite material.
The mean factors' are extracted during the LCIA and the spacer length is extracted from the geometry model. For instance, the environmental impacts generated by the manufacturing of the frame is equal to the product of the frame length, the linear mass and the corresponding impact factors.

K.2 Example 2 : Spacer

The calculation of the spacer mass is a variant of that of the frame. The difference between the two methods lies in the fact that the spacer thickness is not constant, but depends on the gas gap between the panes in the transparent unit. In practice, the spacer height *h* is generally constant, but its thickness *e* is equal to the gas gap thickness between two glass panes. Therefore, the spacer mass is given by

$$M_{Spacer} = {}^{Sec}\overline{M}_{Spacer} \cdot P_j$$

where

${}^{Sec}\overline{M}_{Spacer}$	Sectional mass of the spacer [kg/m/mm]
e_i	Spacer thickness [mm]
P_j	Element perimeter [m]

The calculation of the sectional mass and the environmental impacts of the ‘composite material’ requires a detailed LCIA of the spacer. Table K.2 lists the contribution of the materials constituting an aluminium spacer.

Raw Materials Manufacturing	Volume m3	Masse kg	NRE MJ	GWP kgCO2-equiv.	AP kgSOx-equiv.	POCP kgNOx-equiv.
Aluminum 0% recycled	2.90E-04	7.84E-01	1.37E+02	8.34E+00	5.80E-02	3.75E-03
Butyl (EPDM)	2.64E-04	2.64E-01	2.80E+01	8.56E-01	7.07E-03	4.08E-03
Polysulphid	1.43E-04	1.72E-01	8.41E+00	3.95E-01	1.50E-03	2.64E-03
Desiccant	6.60E-04	6.60E-02	7.19E-01	4.42E-02	1.68E-04	1.13E-04
Total 1	1.36E-03	1.29E+00	1.74E+02	9.64E+00	6.67E-02	1.06E-02
		Mean [Impacts/kg]	**1.35E+02**	**7.49E+00**	**5.19E-02**	**8.23E-03**
		Mean [Impacts/mm/ml]	3.30E+00	1.83E-01	1.26E-03	2.01E-04
	Sectional mass	**2.44E-02**	**[kg/ml/mm]**	(per unit of spacer lenght and spacer width)		

Table K.2 Environmental effects of the manufacturing phase of the constituent materials of a aluminium spacer (spacer length : 4.35 m; spacer width: 12 mm)

As for the frame, the mean impact factors are stored in the database. To perform the LCIA, the length and the thickness of the spacer are extracted from the geometry model, while the sectional mass is extracted from the physical model.

APPENDIX L

MULTIPLICATION FACTOR FOR TRANSPORT IMPACT

The live load of a vehicle corresponds to the maximum mass that a vehicle can transport each journey. Assuming that the mass of material to transport is equal to the live load of a particular means of transport: if the material volume is smaller than the transportable volume, only one journey is required, if it is larger, supplementary journeys will be required as shown in Figure L.1.

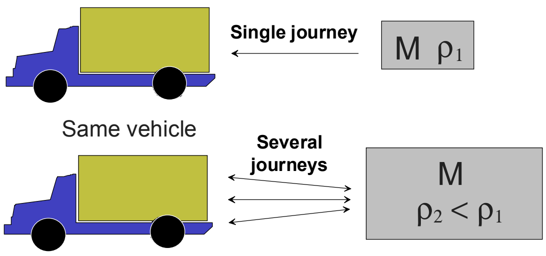


Figure L.1 Influence of the material density on the number of journeys required to transport a material mass (M). If the volume is smaller than the transportable volume, it will require only a single journey (top). If the volume to be transported is bigger, several journeys will be required (bottom).

The transport of a given mass may require more journeys for a light material, such as insulation, than for the same mass of a heavy material, such as concrete. As the density decreases, the material mass becomes smaller for a given material volume. Below a certain density, the mass of transported material is less than the live load transportable by the means of transport. From Table L.1, it can be seen that if the material density exceeds about 300 [kg/m³], the material mass is predominant, and below this value, the volume becomes predominant.

Mean of transport	Live load [t]	Volume [m³]	Limit density [kg/m³]
Lorry 32 t	19	~75	253
Wagon (2 axles)	26	~80	325

Table L.1 Characteristics of means of transport.

To account for this supplementary impact generated during the transport of light material, it is necessary to weight the impact factors of the means of transport by an appropriate factor. The following hypotheses have been made to evaluate the multiplication factor ZF equation:

- The multiplication factor is a step function that represents each supplementary journey.
- If material density ≥ 300 [kg/m³], then ZF = 1
- The slope of the equation is nil for 300 kg/m³, i.e. ZF'(300) = 0
- ZF tends asymptotically to the infinite, when the material density tends to zero.

These assumptions lead to the following equation

$$F = \begin{cases} \dfrac{1}{1440}\cdot\rho + \dfrac{237.5}{\rho} & \textbf{if } \rho < \textbf{300[kg/m³]} \\ 1 & \textbf{if } \rho \geq \textbf{300[kg/m³]} \end{cases} \qquad \text{(L.1)}$$

$$ZF = \text{RoundSup}(F)$$

where

ρ	Material density [kg/m³]
RoundSup	function rounding to the closest upper integer.

The Figure L.2 is a graphical representation of the *ZF* function.

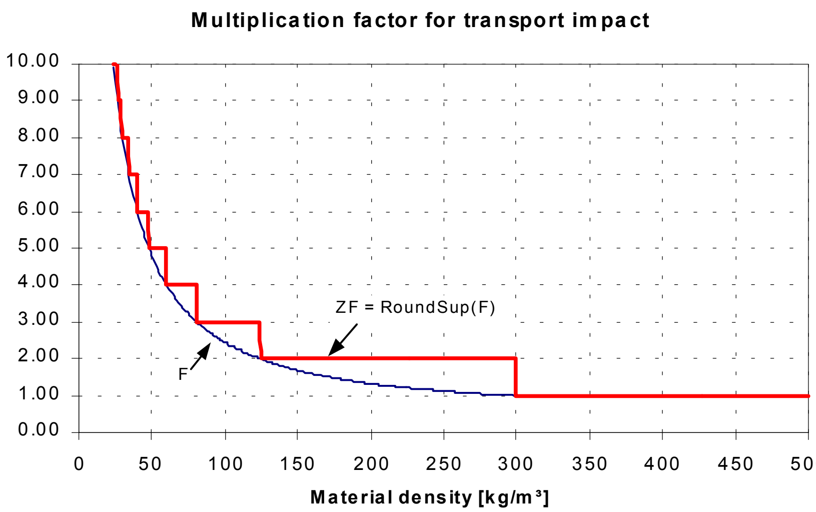


Figure L.2 Multiplication factor *ZF*. **(ZF.xls)**

To illustrate the influence of the transport of a light material on the impact generated by the transportation of a construction, take the example of the roof schematised in Figure L.3.

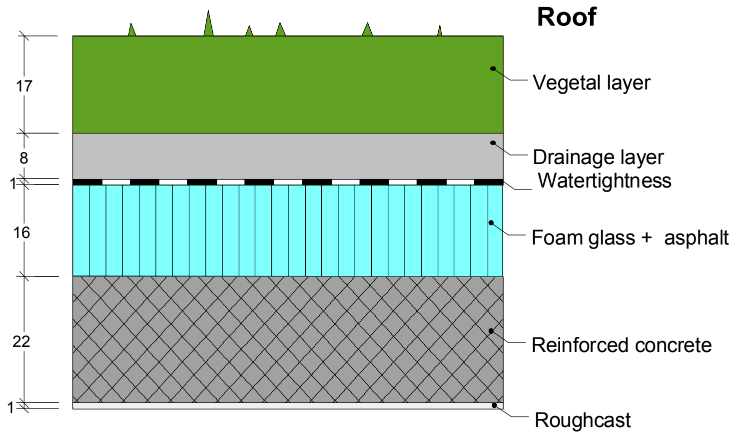


Figure L.3 Roof composition.

Among the different materials that constitute the roof, only the cellular glass has a density < 300 kg/m³. The Figure L.4 represents the global warming potential (GWP) generated during the transport of these construction materials without (left) and with (right) the accounting of the material density.

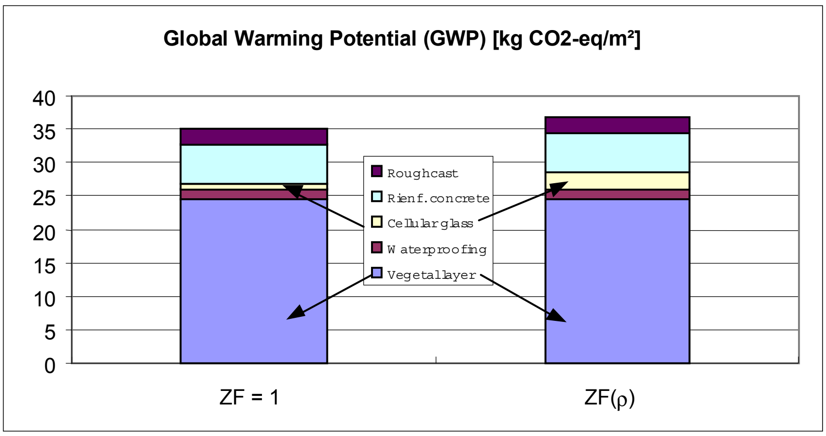


Figure L.4 Global worming potential generated by the roof transportation. The results on the right have been obtained using the ZF function.

As can be observed from Figure L.4, the accounting of the material density triples the impact generated by the cellular glass compared to the situation where the influence is not included (ZF = 1). The impact generated by the other materials is unchanged. In the case of this green roof, the supplementary impact generated by the transport of a light material increases the total impact of the construction by about 3%.

It should be stressed that this multiplication factor is only required for the transport of new material. Waste materials are generally compacted before their transport to the management site to reduce the number of journeys and it is assumed that their density is below the limit density (300 [kg/m³]).

APPENDIX M

REPLACEMENT STRATEGY

This appendix analyses the calculation approach presented in paragraph 5.19 for the appraisal of the impacts generated during the replacement phase, in which the number of replacements Nr_i is given by

$$Nr_i = \begin{cases} \textbf{if } \left((BLS/MSL_i) - \mathrm{INT}(BLS/MSL_i)\right) < 0.5, \textbf{ then } \mathrm{INT}(BLS/MSL_i) - 1 \\ \textbf{if } \left((BLS/MSL_i) - \mathrm{INT}(BLS/MSL_i)\right) \geq 0.5, \textbf{ then } \mathrm{INT}(BLS/MSL_i) \end{cases}$$

where

INT Integer part function, i.e. rounded value at the first lower integer

Nr_i Number of replacements of material i, in years [y]

BLS Building lifetime, in years [y]

MSL_i Service life of material i, in years [y]

It can be inferred from this method that, it is possible to replace a material without influencing the other materials within the construction. In reality, if a material has to be replaced, all the materials from the construction surface to the replaced material that are on the same side of the bearing material would probably be replaced for financial and/or practical reasons as shown in Figure M.1.

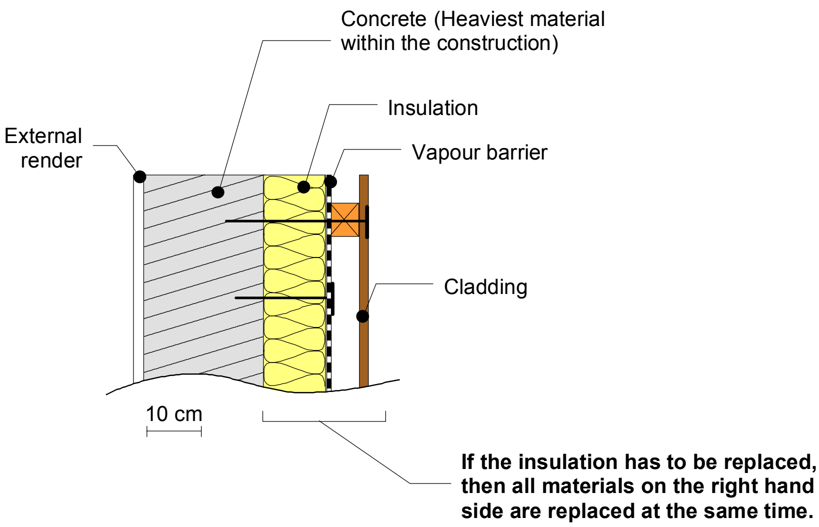


Figure M.1 Part of a construction affected when an internal material is replaced. **(replcement material.dsf)**

Table M.1 lists each construction materials with its corresponding life service and the number of replacements it may require over the building life.

Material	Life service [y] [SIA1995a]	Number of replacements Assuming a building life of 80 years	
		(BLS/MSL-1) => Nr_i	In reality
Wood cladding	35	(1.29) => 1	1
Support bars	35	(1.29) => 1	1
Vapour barrier	35	(1.29) => 1	1
Insulation	35	(1.29) => 1	1
Concrete (bearing structure)	80	0	0
External render	40	(1.00) => 1	1

Table M.1 Comparison of the number of material replacements in a construction based on two different approaches.

The last two columns in Table M.1 give the number of replacements for each material according to the Nr_i model and what may probably occur in the reality. As it can be seen, despite its simplicity, the Nr_i gives satisfactory results.

APPENDIX N

AIR ABSORPTION

This appendix specifies an analytical method for the estimation of the sound absorption coefficient *m*, which is required to predict the absorption due to air in the calculation of the reverberation time. The final expression of *m* is a function of sound frequency, air temperature and humidity.

According to Lienard [Lie1983] the sound coefficient *m* is given by :

$$m = \frac{\alpha^{att}}{4.34} \tag{N.1}$$

where

m sound absorption coefficient [m^{-1}]

α^{att} sound attenuation coefficient [dB/m]

It should be stressed, that α^{att} does not represent a sound absorption coefficient (not the same unit), even if it uses the same notation α. Therefore, to stay consistent and to avoid confusion, this appendix uses the notation with the exponent ^{att} for the sound attenuation coefficient.

According to Harris [Har1966], sound attenuation due to atmospheric absorption is a function of the sound frequency, the temperature, humidity and pressure of the air. It occurs as a consequence of the following two basic mechanisms:

- *Classical absorption*, associated with the conversion of acoustic energy (organised motion associated with the kinetic energy of the molecules) into equivalent heat energy (uncoordinated motion associated with thermal agitation).
- *Relaxation absorption*, associated with the redistribution of internal energy that occurs during the collision of gas molecules.

The attenuation coefficient α^{att}, can be expressed by the sum of the following terms:

$$\alpha^{att} = \alpha_{cl}^{att} + \alpha_{rot}^{att} + \sum_j \alpha_{vib,j}^{att} \tag{N.2}$$

where

α_{cl}^{att} Classical absorption

α_{rot}^{att} Molecular absorption caused by rotational relaxation

$\alpha_{vib,j}^{att}$ Molecular absorption caused by vibrational relaxation of the molecule *j*

The formulation of these three mechanisms is based on the analytical formulas proposed by ISO 9613/1 [ISO1993].

N.1 Classical attenuation and rotational relaxation

The part of attenuation related to the classical and rotational relaxation mechanisms is given by

$$\alpha_{cl}^{att} + \alpha_{rot}^{att} = f^2 \cdot \frac{1.60 \cdot 10^{-10} \sqrt{\frac{T}{T_0}}}{\left(\frac{p}{p_0}\right)} \tag{N.3}$$

where

f	frequency of the sound [Hz]
T	air temperature [°K]
T_r	reference air temperature (293.15) [°K]
p	air pressure [kPa]
p_0	reference air pressure (101.325) [kPa]

It has been shown that the rotational relaxation can change by no more that 2% depending on the water vapour proportion and therefore for the sake of simplification, Eq. (N.3) ignores these effects Bass [Bas1984].

N.2 Vibrational relaxation

The part of the attenuation related to the vibrational relaxation of a molecule j is given by :

$$\alpha_{vib,j}^{att} = f^2 \cdot \left(\frac{4\pi X_j}{35c}\right)\left(\frac{\theta_j}{T}\right)^2 \frac{e^{-\theta_j / T}}{f_{r_j} + (f^2 / f_{r_j})} \tag{N.4}$$

where

f	frequency of the sound, in hertz [Hz]
X_j	molecular fraction of the molecule j, in [-]
θ_j	characteristic vibrational temperature of molecule j, in Kelvin [K]
c	speed of sound, in meters per second [m/s]
f_{r_j}	relaxation frequency of molecule j, in hertz [Hz]

The fractional volumes X_j and the characteristic vibrational temperature θ_j of the principal air constituents are given in Table N.1.

Air constituents	Fractional volume X_j [%]	Vibrational temperature θ_j [K]
Nitrogen	78.084	3352.0
Oxygen	20.948	2239.1
Other	1.215	/

Table N.1 Fractional volumes of dry air at sea level and characteristic vibrational temperature.

The small amount of molecular absorption due to the presence of other constituents (carbon dioxide, ozone, etc.) can be neglected in a first approximation because of their small fractional volume, as shown in Table N.1. Therefore, in this context, only Nitrogen and Oxygen will be considered as air constituents that are predominant in air attenuation mechanisms.
A detailed analysis of the contribution of each mechanism involved in air absorption shows that below a relative humidity of 60%, the predominant mechanism in air absorption is the vibrational relaxation of Oxygen while above that, the predominant mechanism is the vibrational relaxation of Nitrogen [Har1966].

N.3 Speed of sound

Using the ideal gas law, the speed of sound c in air is given by (see for instance [Bas1984]):

$$c = 343.23 \cdot \sqrt{\frac{T}{T_0}} \qquad \text{(N.5)}$$

where

c sound speed [m/s]
T air temperature [°K]
T_0 reference temperature of the air (293.15) [°K]

N.4 Relaxation frequencies

Finally, the relaxation frequencies for Nitrogen f_{rN} and for Oxygen f_{rO} are respectively given by

$$f_{rN} = \frac{p}{p_0}\left(\frac{T}{T_0}\right)^{-1/2}\left(9 + 280h \cdot e^{-4.170\left[\left(\frac{T}{T_0}\right)^{-1/3} - 1\right]}\right) \qquad \text{(N.6)}$$

and

$$f_{rO} = \frac{p}{p_0}\left(24 + 4.04 \cdot 10^4 h \frac{0.02 + h}{0.391 + h}\right) \qquad \text{(N.7)}$$

where

f_r relaxation frequency [Hz]
T air temperature [°K]
T_0 reference air temperature (293.15) [°K]
h molar concentration of water vapour [%]

For a given temperature and pressure, the molar concentration h, may be calculated from

$$h = \frac{h_r \cdot 10^E}{\left(\frac{p}{p_0}\right)} \tag{N.8}$$

with exponent E given by

$$E = -6.8346\left(\frac{T_{0i}}{T}\right)^{1.261} + 4.6151 \tag{N.9}$$

where

h_r	relative humidity [%]
T_{0i}	triple-point isotherm temperature (273.16) [°K]
p	air pressure [kPa]
p_0	reference air pressure (101.325) [kPa]

Finally, by combining equations(N.1) to (N.5), the air absorption coefficient m can be written as:

$$m = 3.68 \cdot 10^{-11} f^2 \left(\frac{p}{p_0}\right)^{-1} \left(\frac{T}{T_0}\right)^{1/2} + \left(\frac{T}{T_0}\right)^{-5/2} \left(\sum_{j=N,O} s_j \cdot e^{\frac{-\theta_j}{T}} \cdot \frac{2f^2}{f_{r_j} + \left(\frac{f^2}{f_{r_j}}\right)} \right) \tag{N.10}$$

with

Molecule	s_j	θ_j
Nitrogen (N)	$s_N = 0.1068$	$\theta_N = 3352.0$
Oxygen (O)	$s_O = 0.0128$	$\theta_O = 2239.1$

and where equations (N.6) and (N.7) give f_{rN} and f_{rO} respectively and equations (N.8) and (N.9) give h.

The frequencies of sound f used in room acoustics correspond to the preferred frequencies of either the one-octave or the one-third-octave band frequencies defined in ISO 266 [ISO1975a]. For computer calculation convenience, the frequencies used in the previous equations are calculated for the exact midband frequencies of one-third-octave band filter using the following expression extracted from ISO 9613/1 [ISO1993]:

$$f = 1'000 \cdot \left(10^{3 \cdot b/10}\right)^k \tag{N.11}$$

where

$b = 1/3$	for one-third-octave band filter
k	integer from -10 to +6

The Table N.2 shows the correspondence between the preferred and the calculated frequencies.

ISO 9613/1	100	126	158	200	251	316	398	501	631	794	1000	1259	1585	1995	2512	3162	3981
ISO 266	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000

Table N.2 Correspondence between the one-third-octave band used for computer simulation.

The accuracy of the sound attenuation coefficient calculation given in Eq (N.11) is estimated to be equal to 10% for variables within the following ranges:

- Relative humidity from 0.5 % to 100 %
- Air temperature from -20 °C to +50 °C
- Atmospheric pressure less than two atmospheres
- Frequency from 50 Hz to 10 kHz

The following representation of the air absorption coefficient m results from a calculation where Eq. (N.9) is used for standard atmospheric pressure, i.e. $p = p_0$. The maximum of the air absorption in Figure N.1 to Figure N.4 is observed when the to the sound frequency corresponds to the relaxation frequency of the Oxygen.

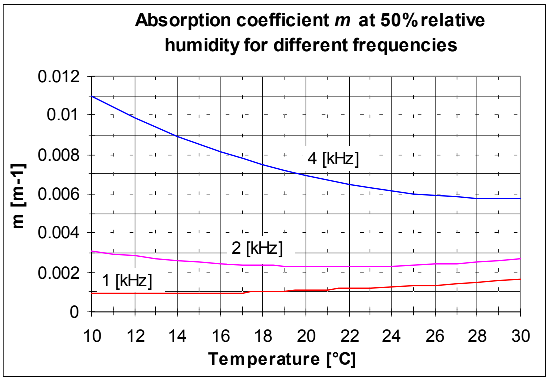


Figure N.1 Absorption coefficient m at 50% relative humidity for different frequencies, as a function of air temperature.

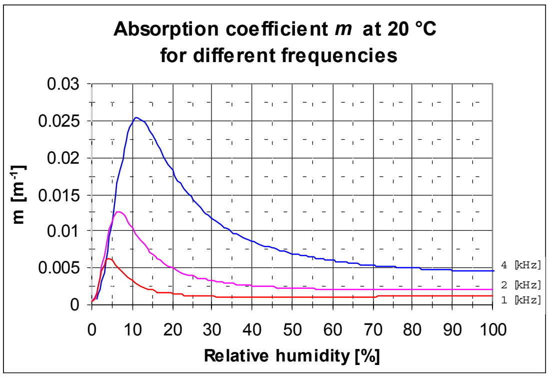


Figure N.2 Absorption coefficient m at 20°C for different frequencies, as a function of relative humidity.

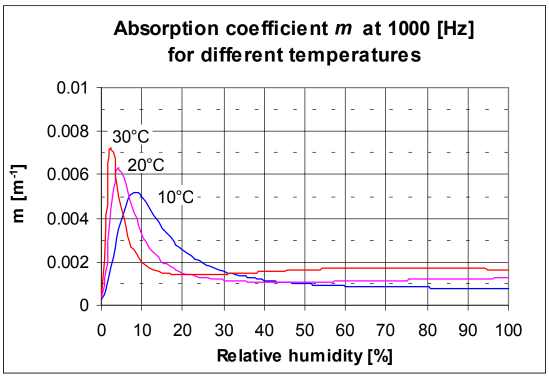


Figure N.3 Absorption coefficient m at frequency 1000 [Hz] for different temperatures, as a function of relative humidity.

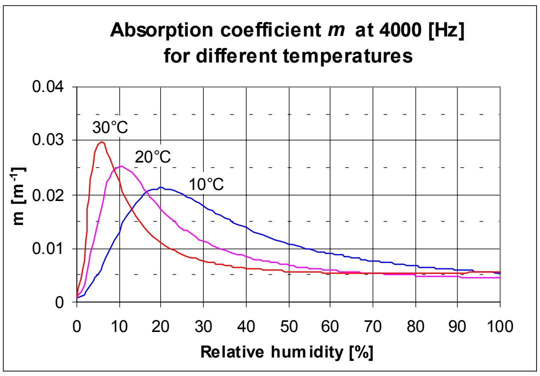


Figure N.4 Absorption coefficient m at frequency 4000 [Hz] for different temperatures, as a function of relative humidity.

For room acoustics applications, it can be seen from these figures that within in the humidity range observed in building (20-80%), the air absorption increases when:

- the frequency increases
- the air temperature increases
- the relative humidity decreases

This behaviour has the consequence, for instance, that the high frequency perception in a conference room with not sufficient ventilation is reduced, because of the rise of the indoor air temperature due to the internal gains generated by the public.

Quantitatively, at 1000 [Hz] and below, the sound absorption coefficient *m*, at the air absorption ($A_f^{Air} = 4m \cdot V$), becomes negligible whatever the air temperature and humidity (see Figure N.3). Between 1000 and 4000 [Hz] the sound absorption decreases by a factor about two when the temperature varies from 10°C to 30°C for a relative humidity between 30 and 80% (Figure N.4).

APPENDIX O

FURNITURE AND OCCUPANT DATA FOR ROOM ACOUSTICS

This appendix specifies the file format used to describe the occupants and the furniture that might be inventoried in the zones of the project. This file is not mandatory, but permit improving the reverberation time calculation by taking into account not only the zone boundaries but also the influence of occupants and furniture. The format *ACO*, used to describe the furniture and the persons, is similar to the format used for the *BCF* file. It is made of two main blocks.

The first block lists the absorption coefficients of the different occupant types and furniture inventoried in the project, while the second block lists the occupant(s) and furniture that might exists in each zone. The Figure O.1 represents the flow chart of the way that the *ACO* file is used during the reverberation time calculation of a zone.

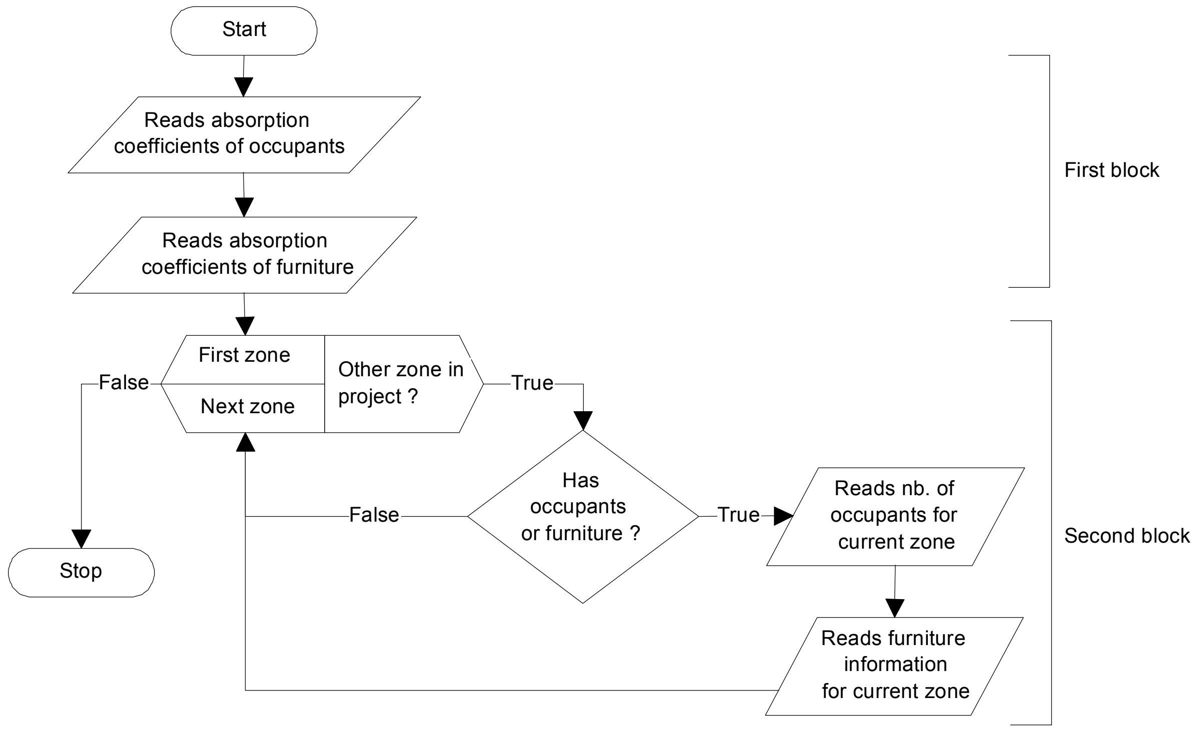


Figure O.1 Structure of the information storing occupants and furniture properties necessary for reverberation time calculation. (aco format.flo)

O.1 First block: Occupants and furniture type description

The first block lists the intrinsic absorption coefficients of the person and furniture that are entered, independently of their location in the project, while the second block describes each zone in the project that has at least one person or piece of furniture.

The first block starts with the occupant type list, which inventories the different types of occupants inventoried in the whole project. The list includes:

- the tag **Occupant_type* followed by
- the number of occupant type(s) existing in the project
  Then for each occupant type:
  - the name (pointer) of the occupant type, and
  - the corresponding absorption coefficients per third octave band.

Then the first block continues with the furniture type list, which includes:

- the tag **Furniture_type* followed by
- the number of furniture types that exist in the project
  Then for each furniture type:
  - the name (pointer) of the furniture type,
  - the type of furniture, and
  - the corresponding absorption coefficients per third octave band.

For the occupant types, it is assumed, that the data are expressed per unit of person(s), i.e. they correspond to the equivalent area, while the furniture is either expressed per unit of furniture (computer, chair, etc.) or per surface area [m²] (cupboard, bed, etc.). The distinction between the two furniture categories is included in the furniture type (*Unit* or *Surf*).

O.2 Second block: Occupants and furniture type in a zone

The second block lists for each zone, the occupants and furniture type(s) that exist in a particular zone. This enables connecting the occupant or furniture type and the corresponding absorption coefficients defined in the first block with the number of occupants or the furniture area in a particular zone.
For each zone that has at least one occupant type or one furniture type, the second block includes per zone:

- the tag **Zone* followed by the zone name in the project
- the tag **Nb_person_type*, followed by the number of occupants type in that current zone
  Then for each occupant type:
  - the person type name (that must correspond to a pointer in the occupant list in the first block) and
  - the number of persons for this occupant type.

The zone information continues with the furniture information, which includes:

- the tag **Nb_furniture_type*, followed by the number of furniture types in that current zone,
  Then for each furniture type:

- ▪ the furniture type name (that must correspond to a pointer in the furniture list in the first block) followed by,
- ▪ either the number of pieces of furniture of that category if the pointer name corresponds to Unit in the furniture list in the first block or the area of this furniture type if the pointer name corresponds to Surf followed by,
- ▪ the surface name hidden by the furniture in the current zone.

The latter data is required to correctly estimate the surface area that effectively absorbs sound. When furniture is in front of a zone's surface, the part of the surface that is hidden does not take part in the absorption process. Therefore, it is necessary to know, in front of which surface the furniture is placed. If no surface name is declared, it is assumed, that the furniture is not in against a zone boundary, as may be the case for a table. If the cross section of the table legs is sufficiently small compared to the floor area, they can be neglected.

The Figure O.2 shows a screen shot of the ESP-r interface, which displays the results of the reverberation time calculation in the meeting room 318 (Zone: F3_318) of the EOS building.

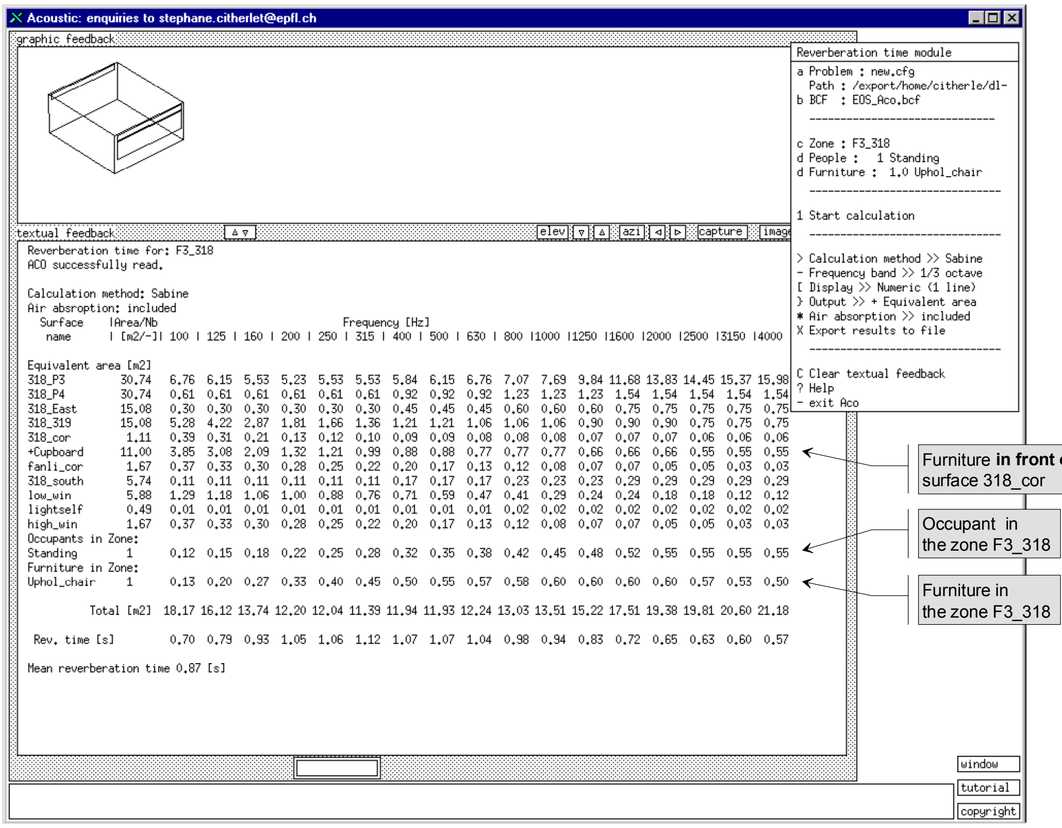


Figure O.2 Example of a furniture in front of a zone boundaries. (Furniture + occupants screen shot.dsf)

The area of the boundary surface *318_cor* is equal to 12.11 [m²], but is hidden by 11.0 [m²] from the furniture *Cupboard* (follow the upper arrow in Figure O.2). As can be seen in the list of equivalent surfaces, the surface area of the furniture *Cupboard*, that is in front of the surface *318_cor*, is deduced from the surface area of the latter. On the other hand, the upholstered chair, which is not in front of a surface (the surface areas of the chair legs are neglected), is listed in the furniture list.

```
# Acoustic  properties of occupants and furniture of the zones in /export/home/citherle/dl-e/eos/zones/new.cfg
#First block
*Occupant_type, 2          # Tag for persons list, number of person categories within the project
# Occupant |               Absorption coefficients persons per frequency [Hz]
      #    type    |            100 |   125 |   160 |   200 |   250 |   315 |   400 |   500 |   630 |   800 |  1000 |  1250 |  1600 |  2000 |  2500 |  3150 |  4000
         Standing,              0.12,   0.15,   0.18,   0.22,   0.25,   0.28,   0.32,   0.35,   0.38,   0.42,   0.45,   0.48,   0.52,   0.55,   0.55,   0.55,   0.55,
Seat_on_chair,                  0.13,   0.20,   0.27,   0.33,   0.40,   0.45,   0.50,   0.55,   0.57,   0.58,   0.60,   0.60,   0.60,   0.60,   0.57,   0.53,   0.50,
#
*Furniture_type, 2# Tag for furniture list, number of different furniture categories within the project
# Furniture |  Cat  |                Absorption coefficients persons per frequency [Hz]
  #    type    |          |         100 |   125 |   160 |   200 |   250 |   315 |   400 |   500 |   630 |   800 |  1000 |  1250 |  1600 |  2000 |  2500 |  3150 |  4000
Uphol_chair,        Unit,           0.13,   0.20,   0.27,   0.33,   0.40,   0.45,   0.50,   0.55,   0.57,   0.58,   0.60,   0.60,   0.60,   0.60,   0.57,   0.53,   0.50,
Cupboard,           Surf,           0.22,   0.20,   0.18,   0.17,   0.15,   0.13,   0.12,   0.10,   0.10,   0.10,   0.10,   0.08,   0.07,   0.05,   0.05,   0.05,   0.05,
#
#Second block
*Zone,                 F3_318                        # Tag, zone name
 *Nb_public_type,      1                             # Tag, number of public types in zone
  Standing,            1,                            # Occupant type, number of instances
*Nb_furniture_type,    2                             # Tag, number of furniture types in zone
  Uphol_chair,         1,          None              # Furniture type, Nb or areas, in front of
 Cupboard,             11.00,      318_cor           # Furniture type, Nb or areas, in front of
#
*Zone,                 F3_319                        # Tag, zone name
*Nb_public_type,       1                             # Tag, number of public types in zone
 Standing,             1,                            # Occupant type, number of instances
*Nb_furniture_type,    2                             # Tag, number of furniture types in zone
 Uphol_chair,    1,    None                          # Furniture type, Nb or areas, in front of
 Cupboard,       9.40, 319_cor                       # Furniture type, Nb or areas, in front of
*End_ACO                                             # End of file
```

Table O.1 Example of a file used for the inventory of furniture and persons in the different zone (line beginning with # are comments).

APPENDIX P

ESTIMATION OF MISSING ABSORPTION COEFFICIENTS

This appendix illustrates the solution retained to assess the sound absorption coefficients of a system, which cannot be found in the literature.

The accuracy of the reverberation time assessment depends on the quality of the absorption coefficients used for the calculation. Many absorption coefficients can be extracted from publications and manufacturers' documentation. In the case of the floor of the EOS building used for a case study in Chapter 7, these data are known for the underside of the EOS floor, which is made of a roughcast finishing on concrete as shown in Figure P.1.

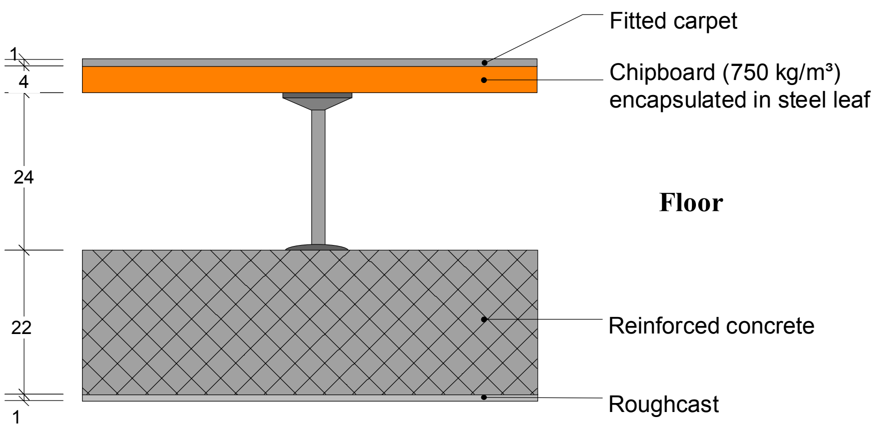
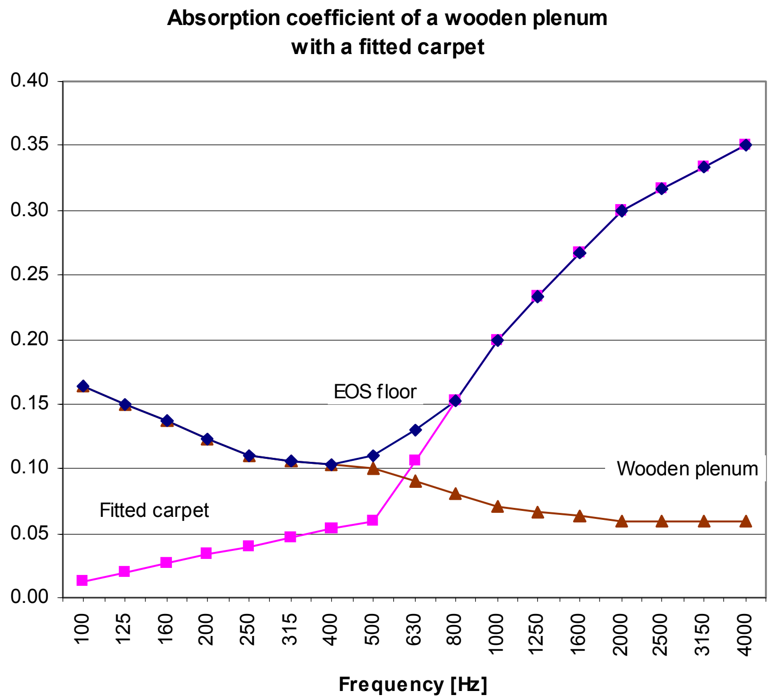


Figure P.1 Floor composition in the EOS building.

For the upper part of the plenum (false-floor), which is made of a wooden plenum covered with a fitted carpet the absorption coefficients were unknown. Rather than to undertake a measurement in a reverberant room (time consuming), the coefficients have been estimated based on simple assumptions.
The sound absorption coefficients of the upside of the EOS floor has been evaluated by using available data published in the literature for:

- Wooden plenum,
- Fitted carpet applied directly on a rigid support such as on a concrete slab

As shown in Figure P.2 the wooden plenum and the fitted carpet have a very different behaviour with regard to the absorption of sound. The plenum structure, made of thick chipboard in front of an air gap plays the role of a membrane and therefore absorbs low frequency sound. On the other hand, the fitted carpet absorbs high frequency due to the size of the enclosed air cavity created by the fibres.



Freq. [Hz]	Fitted carpet on rigid support	Wooden plenum
100	0.01	0.16
125	0.02	0.15
160	0.03	0.14
200	0.03	0.12
250	0.04	0.11
315	0.05	0.11
400	0.05	0.10
500	0.06	0.10
630	0.11	0.09
800	0.15	0.08
1000	0.20	0.07
1250	0.23	0.07
1600	0.27	0.06
2000	0.30	0.06
2500	0.32	0.06
3150	0.33	0.06
4000	0.35	0.06
Reference	[CNA1991]	[Fas1987]

Figure P.2 Estimated sound absorption coefficients of the plenum in the EOS building.

It has been assumed that each mechanism of sound absorption is predominant in the range of frequencies that corresponds to the absorption process. For the EOS plenum, which is made of a fitted carpet on a wooden plenum, the contribution of the wooden plenum is dominant at low frequencies and the contribution of the fitted carpet is dominant at high frequencies. Thus, for a particular frequency, the absorption coefficient has been assumed to be equal to the highest coefficient of both systems, as shown in Figure P.2. The coefficients at 500 and 630 [Hz] have been adapted to smooth the profile shape.

These assumptions, made to estimate the absorption coefficients of an unknown system, might be debatable. But in a first approximation, the absorption coefficients derived from the previous analysis seem to be acceptable. Effectively, the reverberation time measurements undertaken in the two different rooms of the EOS building confirm the calculation results based on the estimated absorption coefficients.

APPENDIX Q

PHYSICAL ATTRIBUTES

This appendix lists all the physical attributes of the materials used in the computer model of the EOS building. The attributes are grouped by view (hygro-thermal, photo-colourimetry, etc.)

Q.1 Material physical attributes

Material Name	View pointer			
	Hygro-thermal (referenced in Q.2)	Photo-colourimetry (referenced in Q.3)	Room acoustics (referenced in Q.5)	LCIA (referenced in Q.6)
Air	*Air*	/	*Calculated*	*Air*
Aluminium (galvanised)	*Aluminium*	*Alu_galva*	*Metal*	*Alu_galva*
Aluminium spacer	*Alu_spacer*	*Alu_galva*	*Metal*	*Alu_spacer*
Argon	*Argon*	/	/	*Argon*
Cellular glass	*Cell_glass*	*Cell_glass*	*CellGlass*	*Cell_glass*
Chipboard	*Chipboard*	*Chipboard*	*MassWood*	*Chipboard*
Clear float glass	*CF_glass*	*Clear_float*	*SglGlazg*	*CF_glass*
Cloth blind	*Cloth_bld*	*Cream_fab*	*LightCur*	*Cloth_bld*
Coated glass	*Coat_glass*	*Clear_float*	*SglGlazg*	*Coat_glass*
Fitted carpet	*Text_floor*	*Fitcarp_med*	*CarpetRS*	*Fitt_carpet*
Glass wool	*Glass_wool*	*Min_insul*	*MW60S*	*Glass_wool*
Granite tile	*Granite*	*Granite_gy*	*ConTile*	*Granite*
Low-emissivity film	*Lowe_film*	*Clear_float*	*LightCur*	*Lowe_film*
Plaster board	*Plast_Brd*	*Plaster_bd*	*Plaster*	*Plaster_brd*
PVC frame	*PVC_frame*	*PVC_frame*	*PVC*	*PVC_frame*
Reinforced concrete for facade	*Conc_Fac*	*Grey_concr*	*RoughCon*	*RienConF*
Reinforced concrete for slab	*Conc_slab*	*Grey_concr*	*RoughCon*	*RienConS*
Roughcast (Internal)	*Int_rend*	*Whit_roughca*	*Roughcast*	*Rough_Int*
Steel	*Steel*	*Steel*	*Metal*	*SteelSheet*
Vegetal layer	*Wet_sand*	*Earth_grass*	*Gravel*	*Veg_layer*
Waterproofing	*Waterproof*	*Polymer_blck*	*Rubber*	*Polymer_film*

Q.2 Hygro-thermal

Name	Pointer	Description	Life Time [y]	Conduct. [W/(mK)]	Density [kg/m^3]	Specific heat [J/(kg·K)]	Vapor resist. -	Emissi. -	Solar absor. -	Rough. -	Specul. -	Reference
Air	*Air*	Air	10000	0.03	1.2	1008	1	0.00	-	-	-	ACCCCXXX
Aluminium	*Aluminium*	Aluminium alloy, rough polished	40	160	2'800	880	999'999	0.22	0.06	0.2	0.3	ACCCCCEFF
Aluminium spacer	*Alu_spacer*	Aluminium spacer	30	120	947	1000	999'999	0.22	0.08	0.00	0.00	AZZZBBDFF
Argon	*Argon*	Argon for window	30*	0.02	1.7	519	1	0.00	-	-	-	ACCCCXXX
Cellular glass	*Cell_glass*	Cellular glass 120 kg/m^3 + bitume	40	0.05	120	800	75'000	0.96	0.88	0.00	0.00	HBBBBFFF
Chipboard	*Chipboard*	Particle board (chipboard) 500 kg/m^3	35	0.14	500	1700	50	0.90	0.78	0.00	0.00	ACCCCCEFF
Clear float glass	*CF_glass*	Clear float glass	30	1.0	2500	720	999'999	0.93	0.08	0.00	0.00	ABBBBBEFF
Cloth blind	*Cloth_bld*	Polyamide with 25% glass fibre	30*	0.30	1'450	1600	50'000	0.96	0.60	0.00	0.00	ACCCCCFFF
Coated glass (5%)	*Coat_glass*	Coated glass (5%)	30	1.0	2500	720	999'999	0.05	0.08	0.00	0.00	ABBBBBEFF
Glass wool	*Glass_wool*	Glass fibre panel 20-60 kg/m^3 (un-compres.)	30	0.04	40	600	2	0.96	0.60	0.00	0.00	ABBBBFFF
Granite	*Granite*	Granite	80	3.50	2'800	900	10'000	0.90	0.55	0.01	0.03	ABBBBBEFF
Internal rendering	*Int_rend*	Internal mortar rendering 1400 kg/m^3	40	0.70	1'400	900	8	0.90	0.73	0.00	0.00	ABBBBBEFF
Krypton	*Krypton*	Krypton gas for glazing unit	30	0.009	3.6	245	1	1.00	-	-	-	ACCCCXXX
Low-e film	*Lowe_film*	Low emissivity film (Heat mirror) for windows made of PET	30*	0.30	1'450	1600	50'000	0.05	0.60	0.00	0.00	GGGGGGGFF
Plaster board	*Plast_Brd*	Plaster board	30	0.40	1'000	800	8	0.92	0.50	0.00	0.00	ABBBBBFFF
PVC board	*PVC*	PVC	30*	0.2	1390	900	50'000	0.96	0.60	0.00	0.00	ACCCCCEFF
PVC frame	*PVC_frame*	PVC frame	30*	37.4	2585	702	999'999	0.96	0.60	0.00	0.00	AZZZBBDFF

Hygro-thermal (continue)

Name	Pointer	Description	Life Time	Conduct.	Density	Specific heat	Vapor resist.	Emissi.	Solar absor.	Rough.	Specul.	Reference
			[y]	[W/(mK)]	[kg/m³]	[J/(kg·K)]	-	-	-	-	-	
Reinf. concrete for facade	*Conc_Fac*	Reinforced concrete for facade CP300-350	80	2.50	2'400	1000	120	0.93	0.65	0.00	0.00	ACCCCCEFF
Reinf. concrete for slab	*Conc_slab*	Reinforced concrete for slab CP300-350	80	2.30	2'300	1000	120	0.93	0.65	0.00	0.00	ACCCCCEFF
Roughcast (internal)	*Int_rend*	Internal mortar rendering 1400 kg/m³	40	0.70	1'400	900	8	0.90	0.73	0.00	0.00	ABBBBBEFF
Steel	*Steel*	Steel	40	60	7'850	500	999'999	0.15	0.55	0.00	0.00	ABBBBBEFF
Textile flooring	*Text_floor*	Carpet, textile flooring	10	0.06	200	1300	5	0.94	0.65	0.00	0.00	ACCCCCFFF
Waterproof	*Waterproof*	Waterproof membranes for flat roofs, 1 cm	25	0.20	1'200	1600	8'000	0.91	0.88	0.00	0.00	ABBBBBEFF
Wet, sandy soil	*Wet_sand*	Wet, sandy soil for flat roof	40	1.40	1'800	900	4	0.90	0.76	0.00	0.00	ABBBBBEFF

Code	**Reference**
A	D0123 [SIA1995a]
B	SIA 381/1 [SIA1980]
C	CEN 12524 [CEN1989]
D	Solar absorption: http://www.tak2000.com/data/finish.htm
E	Thermal and Acoustic Insulation, R.M.E. Diamant, ed. Butterworths, London, 1986
F	LESO-PB, Measurements made at the Building Physics Laboratory at the Swiss federal Institute of Technology(LESO-PB), Lausanne, Switzerland
G	Sofraver SA, Mr. Grandchamp, route de Rosé 37 (Avry-sur-Matran) , 1754 Rosé FR, Switzerland, Phone: (026) 470 45 10
H	Pittsburgh Corning, Mr. Fressineau, route de Denges 28G , 1027 Lonay VD , Switzerland, Phone: (079) 209 21 11
X	No data required
Z	Author's estimation
*	*Same life time as other window material

Q.3 Photo-colourimetry

Name	Pointer	Description	Reflec.	r	g	b	Reference
Aluminium (galvanished)	*Alu_galva*	Aluminium (galvanised)	0.66	0.62	0.67	0.69	AAAAAA
Cellular glass (black)	*Cell_glass*	Cellular glass (glass)	0.04	0.05	0.04	0.03	AAAAAA
Cement brick (grey)	*Cement_brick*	Cement brick	0.29	0.36	0.27	0.23	AAAAAA
Chipboard (medium brown)	*Chipboard*	Chipboard (medium brown)	0.31	0.42	0.28	0.14	AAAAAA
Clear float glass	*Clear_float*	Clear float glass 4 mm	0.93	0.88	0.88	0.88	AAAAAA
Concrete (medium grey)	*Grey_concr*	Medium grey concrete	0.20	0.24	0.19	0.15	AAAAAA
Earth and grass	*Earth_grass*	Earth and grass (Brown-green)	0.06	0.07	0.06	0.03	AAAAAA
Fitted carpet (medium grey)	*Fitcarp_med*	Fitted carpet (medium grey)	0.17	0.18	0.17	0.16	AAAAAA
Glass wool (light yellow)	*Min_insul*	Glass wool (light yellow)	0.64	0.74	0.64	0.23	AAAAAA
Granite (grey)	*Granite_gy*	Granite (grey)	0.21	0.21	0.21	0.20	AAAAAA
Gravel	*Clear_gravel*	Cream-white gravel	0.38	0.45	0.37	0.26	AAAAAA
Plaster board	*Plaster_bd*	Plaster board (un-coated)	0.68	0.70	0.67	0.66	AAAAAA
Polymer (black)	*Polymer_blck*	Black polymer such as rubber or waterproofing.	0.07	0.07	0.07	0.07	AAAAAA
PVC frame (white)	*PVC_frame*	White PVC frame	0.80	0.81	0.80	0.75	AAAAAA
Roughcast (white)	*Whit_roughca*	White roughcast	0.71	0.73	0.71	0.63	AAAAAA
Stratified PVC (medium grey)	*Strati_grey*	Stratified (medium grey)	0.51	0.51	0.51	0.50	AAAAAA
Steel	*Steel*	Natural steel	0.44	0.46	0.43	0.40	AAAAAA
Textile blind (cream)	*Cream_fab*	Cream-textile blind	0.61	0.71	0.59	0.52	AAAAAA

Code	**Reference**
A	LESO-PB, Measurements made at the Solar Energy and Building Physics Laboratory (LESO-PB), Switzerland

Q.4 Optics

Internal_window	Angles of incidence (0° = perpendicular to the surface)					Reference
	0	40	55	70	80	
Visible transmission of whole glazing system	0.781	-	-	-	-	AAAAAA
Solar transmission of whole glazing system	0.604	0.572	0.508	0.353	0.155	AAAAAA
Solar absorption of:						
- External pane	0.163	0.178	0.193	0.211	0.211	AAAAAA
- Air gap	0.001	0.001	0.001	0.001	0.001	AAAAAA
- Internal pane	0.12	0.128	0.127	0.113	0.078	AAAAAA

Superglass	Angles of incidence (0° = perpendicular to the surface)					Reference
	0	40	55	70	80	
Visible transmission of whole glazing system	0.623	-	-	-	-	AAAAAA
Solar transmission of whole glazing system	0.337	0.316	0.27	0.157	0.055	AAAAAA
Solar absorption of:						
- External pane	0.117	0.128	0.139	0.152	0.152	AAAAAA
- Air gap	0.001	0.001	0.001	0.001	0.001	AAAAAA
- Internal pane	0.035	0.037	0.036	0.027	0.015	AAAAAA

Code	**Reference**	
A	WIS	[WIS1996]

Q.5 Room acoustics

Name	Pointer	Description	Type	Unit	Frequency [Hz]																	Ref.
					100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	
Materials																						
Carpet on plenum	*Carplenum*	Fitted carpet 7-10 mm on plenum	Mat.	m²	0.22	0.20	0.18	0.17	0.18	0.18	0.19	0.20	0.22	0.23	0.25	0.32	0.38	0.45	0.47	0.50	0.52	F
Cellular glass	*CellGlass*	Cellular glass(140 kg/m³)	Mat.	m²	0.03	0.04	0.05	0.05	0.06	0.09	0.13	0.16	0.17	0.18	0.19	0.19	0.19	0.19	0.20	0.22	0.23	B
Concrete tiling	*ConTile*	Concrete tiling	Mat.	m²	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.03	0.04	0.04	0.04	0.05	0.05	0.05	0.05	0.05	B
Concrete (rough)	*RoughCon*	Rough concrete, stripping formwork	Mat.	m²	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.03	B
Curtain (light)	*LightCur*	Light curtains (25% folded)	Mat.	m²	0.02	0.04	0.10	0.17	0.23	0.29	0.35	0.41	0.46	0.52	0.57	0.56	0.54	0.53	0.49	0.44	0.40	A
Fitted carpet	*CarpetRS*	Fitted carpet 7-10 mm on rigid support	Mat.	m²	0.03	0.04	0.05	0.06	0.07	0.09	0.10	0.12	0.18	0.24	0.30	0.37	0.43	0.50	0.60	0.70	0.80	B
Glazing (double)	*Dgz4-12-4*	Double galzing 4/12/4 (closed)	Com.	m²	0.22	0.20	0.18	0.17	0.15	0.13	0.12	0.10	0.08	0.07	0.05	0.04	0.04	0.03	0.03	0.02	0.02	A
Glazing (single)	*SglGlazg*	Single glazing (Closed)	Mat.	m²	0.07	0.06	0.05	0.05	0.04	0.04	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	A
Gravel	*Gravel*	Gravel 100 mm	Mat.	m²	0.03	0.25	0.37	0.48	0.60	0.62	0.63	0.65	0.67	0.68	0.70	0.72	0.73	0.75	0.77	0.78	0.80	
Marble	*Marble*	Marble and other smotth stone	Mat.	m²	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.03	B
Metal	*Metal*	Thick (rigid) metal surface (metal sheet infront of a rigid surface	Mat.	m²	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	D
Mineral wool	*MW60S*	Dense mineral wool (85 kg/m3 - 60 mm) on support- no fiber glass net (TOPA)	Mat.	m²	0.40	0.45	0.65	0.83	0.94	1.02	1.06	0.97	0.95	1.02	1.08	1.01	1.01	1.02	1.01	1.00	1.00	C
Plaster	*Plaster*	Thick (rigid) plaster facing	Mat.	m²	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.04	0.04	0.04	0.05	0.05	0.06	0.07	0.08	D

Name	Pointer	Description	Type	Unit	Frequency [Hz]																	Ref.
					100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	
Materials (continue)																						
PVC (rigid)	*PVC*	PVC	Mat.	m²	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.04	0.04	0.05	0.05	0.06	0.06	0.05	0.05	A
Roughcast	*Roughcast*	Standard roughcast on masonry or concrete	Mat.	m²	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.03	0.04	0.04	0.04	0.05	0.05	0.05	0.05	0.05	A
Rubber	*Rubber*	Caoutchouc, Rubber	Mat.	m²	0.03	0.03	0.03	0.04	0.04	0.05	0.05	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	B
Steiner partition	*SteelPart*	PVC film + Steel sheet 6mm + Plasterboard 12.5 mm + Mineral wool (96 kg/m³] 50 mm	Com.	m²	0.35	0.27	0.20	0.12	0.11	0.09	0.08	0.08	0.07	0.07	0.07	0.06	0.06	0.06	0.05	0.05	0.05	F
Wood door	*WooDoor*	Wood door	Mat.	m²	0.22	0.20	0.18	0.17	0.15	0.13	0.12	0.10	0.10	0.10	0.10	0.08	0.07	0.05	0.05	0.05	0.05	A
W ood (massif)	*MassWood*	Massif wood or wood board on rigid support	Mat.	m²	0.04	0.04	0.04	0.04	0.04	0.04	0.05	0.05	0.05	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	B
Person & Furniture																						
Adult on upholstered seat	*AdultUph*	Adult on a upholstered seat	Per.	pers.	0.13	0.20	0.27	0.33	0.40	0.45	0.50	0.55	0.57	0.58	0.60	0.60	0.60	0.60	0.57	0.53	0.50	A
Cupboard	*Cupboard*	Cupboard	Mat.	m²	0.22	0.20	0.18	0.17	0.15	0.13	0.12	0.10	0.10	0.10	0.10	0.08	0.07	0.05	0.05	0.05	0.05	A
Desk (office)	*Desk_off*	Office desk (per unit)	Fur.	unit	0.53	0.50	0.47	0.43	0.40	0.42	0.43	0.45	0.45	0.45	0.45	0.50	0.55	0.60	0.63	0.67	0.70	G
Standing person	*StandPers*	Standing person	Per.	pers.	0.12	0.15	0.18	0.22	0.25	0.28	0.32	0.35	0.38	0.42	0.45	0.48	0.52	0.55	0.55	0.55	0.55	A

Code	**Reference**
A	CNA [CNA1991]
B	Fasold [Fas1987]
C	Flumroc [Flu1999]
D	Database of CATT-Software, November 2000
E	Isover [ISOVER1999]
F	Measurements made at the laboratoire d'Energie Solaire et de Physique du Bâtiment, Lausanne, Switzerland
G	Templeton [Tem1993]

Q.6 Environmental impacts

Name	Pointer	Manufacturing (referenced in Q.7)	Transport to construction site			Transport to building site			Reference
			Distance	Mean (referenced in Q.10)	Break & loss	Distance	Mean (referenced in Q.10)	Break & loss	
		[pointer]	[km]	[pointer]	[%]	[km]	[pointer]	[%]	
Air	*Air*	X	X	X	X	X	X	X	XXXXXX
Aluminium (galvanised)	*Alu_galva*	Alum_sheet	200*	Lorry16t	1	X	X	X	BBBXXX
Aluminium spacer	*Alu_spacer*	AluSpace	640	Lorry28t	1	160*	Lorry16t	3	ADDYDD
Argon	*Argon*	Argon	100	Lorry28t	0	160*	Del_vehic	0	DDDDDD
Cellular glass	*Cell_glass*	CelGlass	150 +100*	Train Lorry16t	0	X	X	X	EEEXXX
Chipboard	*Chipboard*	Chipbrd	80	Lorry16t	0	X	X	X	NNNXXX
Clear float glass	*CF_glass*	ClrFloat	700	Lorry28t	3	160*	Lorry16t	3	DDDDDD
Cloth blind	*Cloth_bld*	Cloth_bld	544	Lorry28t	0	120*	Lorry16t	0	AJJJJJ
Coated glass	*Coat_glass*	CoatGlas	700	Lorry28t	3	160*	Lorry16t	3	DDDDDD
Fitted carpet	*Fitt_carpet*	SyntFib	160*	Del_vehic	0	X	X	X	KKKXXX
Glass wool	*Glass_wool*	Glaswool	150 +100*	Train Lorry16t	0 0	X	X	X	LLLXXX
Granite tile	*Granite*	Granite	70 + 450 + 550	Lorry28t SeeBoat Lorry28t	0 0 0	60*	Lorry16t	1	PPPPPP
Low-emmissivity film	*Lowe_film*	Low_e_film	50 + 9500 + 95	Lorry28t Fret_plane Lorry28t	0 0 0	160*	Lorry16t	3	CCCCCC
Plaster board	*Plaster_brd*	PlasBrd	100*	Lorry16t	2	X	X	X	NNNXXX
PVC board	*PVC*	PVC	350	Lorry28t	0	X	X	X	
PVC frame	*PVC_frame*	PVCFrame	390	Lorry28t	1	160*	Lorry16t	3	ADDDDD
Reinfor. concrete for slab	*Con_fac*	RienConS	30*	Lorry16t	1	X	X	X	GGGXXX
Reinfor. concrete for facade	*Con_slab*	RienConF	30*	Lorry16t	1	X	X	X	GGGXXX
Roughcast (Internal)	*Rough_Int*	Roughcst	100*	Del_vehic	0	X	X	X	NNNXXX
Steel	*SteelSheet*	StssSteel	400*	Lorry16t	0	X	X	X	BBBXXX
Vegetal layer	*Veg_layer*	Sand	10 +800 +120*	Lorry28t SeeBoat Lorry14t	0 1 0	X	X	X	QQQXXX
Waterproofing	*Polymer_film*	Wattight	300*	Lorry16t	0	X	X	X	FFFXXX

Source	Reference	
A	LESO-PB	Calculation made at the Building Physics Laboratory at the Swiss federal Institute of Technology, Lausanne, Switzerland
B	Debrunner SA	Mr. Chappuis, route de Bussigny 29 , 1023 Crissier VD, Switzerland , Phone: +41 +21 637 52 38
C	Sofraver SA	Mr. Grandchamp, route de Rosé 37 , 1754 Rosé FR, Switzerland, Phone: +41 +26 470 45 10
D	Heglas Bulle SA	Mr. Rime, rue de l'Etang 17, 1630 Bulle FR, Switzerland, Phone: +41 +26 919 66 80
E	Pittsburgh Corning	Mr. Fressineau, route de Denges 28G , 1027 Lonay VD , Switzerland, Phone: +41 +21 79 209 21 11
F	Sarnafil SA	Mr. Pillon, rue de Lausanne 14 , 1030 Bussigny-près-Lausanne VD, Switzerland , Phone: Tel. +41 +21 703 22 00
G	Bétonfrais SA	Mr. Nicole, 1422 Grandson VD, Switzerland , Phone: Tel. +41 +24 445 81 11
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K	Forbo	Forbo Teppichwerke SA, 1003 Lausanne VD, Switzerland, Phone: +41 +21 323 30 02
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O	Flumroc SA	Mr. Niederberger, chemin de Dallaz 3 , 1030 Bussigny-près-Lausanne VD , Switzerland, Phone: +41 +21 701 57 41
P	Rossier SA	Marbrerie ravalements de façades , chemin des Trois-Ponts , 1024 Ecublens VD , Switzerland, Phone: +41 +21 634 16 85
Q	Alpavert SA	Mr. Grossrieder, au Village , 1628 Vuadens FR , Switzerland, Phone: +41 +26 913 75 40
R	Usine des Cheneviers	M. Amman , route de Verbois 40 , 1288 Aire-la-Ville GE , Switzerland, Phone: +41 +22 727 12 00
Y	Estimation	Estimated data from various sources
-	Data not relevant	
*	The transport distance correspond to twice the real distance, as this mean of transport go back empty at contrary to the other mean(s)	

Q.7 Material manufacturing

Name	Pointer	Description	Unit	Life service [year]	Assembl. loss [%]	Spec. 1 [/]	Spec. 2 [/]	NRE [MJ]	GWP [kg CO2-eq.]	AP [kg SOx-eq.]	POCP [kg C2H4-eq.+ NOx]	Ref.
Aluminium 0% recycled	*Alu0*	Aluminium sheet 0% recycled UCPTE	kg	40	**3**	S	/	1.747E+02	1.064E+01	7.393E-02	1.972E-02	3BAX2222
Aluminium 100% recycled	*Alu100*	Aluminium sheet 0% recycled UCPTE	kg	40	**3**	S	/	1.824E+01	1.095E+00	4.490E-03	1.467E-03	3BAX2222
Alum. spacer	*AluSpace*	Aluminium spacer. Data are given per length (ml) and thickness (mm). It includes, the desiccant and the joints impacts	kg	40	1	P	0.006	1.354E+02	7.494E+00	5.187E-02	8.234E-03	3AAAAAAA
Argon	*Argon*	Argon gas used for window filling, with a life time equal to the window life time.	kg	30	2	S	/	3.989E+00	1.883E-01	1.328E-03	2.711E-04	3CAX2222
Cellular glass	*CelGlass*	Cellular glass. It includes the bitume required to glue the board to the support. 2/3 cellular glass + 1/3 of bitume. D0123 (9.03+8.02) UCPTE/CH. For PS = PS for EPS fabrication	kg	30	3	S	/	6.213E+01	2.622E+00	2.078E-02	1.179E-02	3NAXAAAA
Chipboard	*Chipbrd*	Chipboard D0123 (5.04) UCPTE	kg	35	10	S	/	6.500E+00	4.990E-01	3.180E-03	1.651E-03	3NAX1112
Clear float glass	*ClrFloat*	Clear float glass pane	kg	30	7	S	/	1.440E+01	1.027E+00	2.310E-03	1.136E-03	3DAX2222
Cloth blind	*Cloth_bld*	Cloth blind including framework (rails, etc.)	kg	15	15	S	/	1.962E+02	1.195E+01	8.247E-02	5.464E-03	3JAXAAAA
Coated glass	*CoatGlass*	Coated glass pane	kg	30	7	S	/	1.505E+01	1.057E+00	2.517E-03	1.179E-03	3DAX2222
EPDM	*EPDM*	EPDM, Butyl	kg	30	2	S	/	1.059E+02	3.237E+00	2.674E-02	2.103E-02	3DAX2222
Frame (PVC)	*PVCFrame*	PVC frame. Data are given per length (ml) and thickness (mm). It includes, the hinges, the handle and the rails.	kg	30	5	P	0.004	3.083E+01	3.482E+00	1.863E-02	2.402E-03	3DAXAAAA
Granite	*Granite*	Data is not yet available for granite. It has been assumed that granite correspond to limestone impacts multiple by two to take into account the polishing phase (ref. ESU)	kg	40	1	S	/	2.153E-01	1.291E-02	6.910E-05	2.744E-05	3PAXAAAA

Name	Pointer	Description	Unit	Life service [year]	Assemb. loss [%]	Spec. 1 [/]	Spec. 2 [/]	NRE [MJ]	GWP [kg CO2-eq.]	AP [kg SOx-eq.]	POCP [kg C2H4-eq.+ NOx]	Ref.
Glasswool.	*Glasswool*	Glass wool insulation (from 13 to 112 kg/m³) UCPTE/CH	kg	30	4	S	/	1.870E+01	1.479E+00	9.494E-03	2.526E-03	3LAX2222
Low-e film	*Low_e_film*	Heat Mirror low emissivity film made of PET (0% recycled). The fabrication impacts includes, the PET fabrication + low-e coating. This latest correspond to the fabrication impacts of (coated glass - clear float glass) based on source 2	kg	30	5	S	/	1.231E+02	3.790E+00	2.541E-02	3.521E-02	CCAXAAAA
Plasterboard	*PlastBoard*	Plasterboard D0123 (1.14) UCPTE	kg	30	3	S	/	4.800E+00	3.180E-01	2.050E-03	5.281E-04	3NAX1112
PVC	*PVC*	PVC	kg	40	3	S	/	8.443E+01	3.931E+00	2.424E-02	8.917E-03	3AAX2222
PUR	*PUR*	Polyurethane hard foam	kg	30	2	S	/	1.020E+02	1.375E+01	5.965E-02	1.150E-02	3AAX2222
Rienforced concrete for slab	*RienConS*	Reinforced concrete for horizontal slab construction. Include the steel wiring (5%)	kg	80	1	S	/	1.400E+00	1.570E-01	5.780E-04	5.780E-04	3NAX2222
Rienforced concrete for facade	*RienConF*	Reinforced concrete for facade construction. Include the steel wiring (8%)	kg	80	1	S	/	1.769E+00	1.670E-01	6.520E-04	6.520E-04	3NAX2222
Synthetic fiber	*SyntFib*	Synthetic fiber (polyesther 100 kg/m³) D0123 (8.05) UCPTE & Polypropylen for PS. Can be used ofr fitted carpet.	kg	10	10	S	/	1.156E+02	3.562E+00	2.306E-02	5.532E-02	3KAX1112
Roughcast (internal)	*Roughcast*	Conventional internal roughcast (84%gravel, 10% cement, 4%Hydro. Gips, 2% inciner. Gips + mixing) UCPTE-mix	kg	35	10	S	/	1.500E+00	1.940E-01	6.900E-04	5.173E-04	3NAX2222
Sand / gravel	*Sand*	Sand / gravel for construction UCPTE/CH	kg	30	1	S	/	1.562E-01	1.002E-02	5.114E-05	4.455E-05	3NAX2222
Steel	*Steel*	Steel CH/UCPTE	kg	25	3	S	/	3.834E+01	2.224E+00	8.639E-03	3.079E-03	3BAX2222
Stainless steel	*StssSteel*	Stainless steel CH/UCPTE	kg	25	3	S	/	9.565E+01	5.710E+00	3.503E-01	9.949E-03	3BAX2222
Polymerbitume	*Polymerbit*	Polymerbitume D0123 (8.03) UCPTE. Used for waterproofing (flat roof).	kg	25	3	S	/	5.010E+01	1.048E+00	6.480E-03	2.103E-02	3BAX1112

Code	Reference	
1	D0123	[SIA1995a]
2	Weibel	[Wei1995]
3	OCF	[OCF1995]
A	LESO-PB	Calculation made at the Building Physics Laboratory at the Swiss federal Institute of Technology, Lausanne, Switzerland
B	Debrunner SA	Mr. Chappuis, route de Bussigny 29 , 1023 Crissier VD, Switzerland , Phone: +41 +21 637 52 38
C	Isover SA	Mr. Grandchamp, route de Rosé 37 , 1754 Rosé FR, Switzerland, Phone: +41 +26 470 45 10
D	Heglas Bulle SA	Mr. Rime, rue de l'Etang 17, 1630 Bulle FR, Switzerland, Phone: +41 +26 919 66 80
E	Pittsburgh Corning	Mr. Fressineau, route de Denges 28G , 1027 Lonay VD , Switzerland, Phone: +41 +21 79 209 21 11
F	Sarnafil SA	Mr. Pillon, rue de Lausanne 14 , 1030 Bussigny-près-Lausanne VD, Switzerland , Phone: Tel. +41 +21 703 22 00
G	Bétonfrais SA	Mr. Nicole, 1422 Grandson VD, Switzerland , Phone: Tel. +41 +24 445 81 11
H	Sotrag	Mr.Cochevnikov, rue du Petit-Chêne 30 , 1003 Lausanne VD, Switzerland , Phone: +41 +79 44 74 101
I	BIRD	Mr. Martaler, route de Renens 2, 1008 Prilly VD, Switzerland , Phone: +41 +21 624 64 94
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K	Forbo	Forbo Teppichwerke SA, 1003 Lausanne VD, Switzerland, Phone: +41 +21 323 30 02
L	Flumroc SA	Mr. Niederberger, 1024 Ecublens, Switzerland, Phone: +41 +21 691 21 61
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P	Rossier SA	Marbrerie ravalements de façades , chemin des Trois-Ponts , 1024 Ecublens VD , Switzerland, Phone: +41 +21 634 16 85
Y	Estimation	Estimated data from various sources
X	Not relevant	

Q.8 Material elimination

Name	Disposal process												Ref.
	Recycling				Incineration				Landfill				
	Rate [%]	Distance [km]	Mean (referenced in Q.10) [pointer]	Process (referenced in Q.9) [pointer]	Rate [%]	Distance [km]	Mean (referenced in Q.10) [pointer]	Process (referenced in Q.9) [pointer]	Rate [%]	Distance [km]	Mean (referenced in Q.10) [pointer]	Process (referenced in Q.9) [pointer]	
Air	100	-	-	-	0	-	-	-	0	-	-	-	A--- ---- ----
Aluminium (galvanished)	85	200*	Lorry16t	-	0	-	-	-	15	100*	Lorry16t	StabWst	BBBB B--- BRRB
Aluminium spacer	0	-	-	-	0	-	-	-	100	100*	Lorry16t	StabWst	D--- D--- DRRD
Argon	100	-	-	-	0	-	-	-	0	-	-	-	A--- ---- ----
Cellular glass	95	100* + 150	Lorry16t Train	-	0	-	-	-	5	100*	Lorry16t	InertWst	EERE E--- ERRR
Chipboard	50	80	Lorry16t	-	50	100*	Lorry16t	MixWood	0	-	-	-	I RRA I RRR R---
Clear float glass	85	100*	Lorry16t	-	0	-	-	-	15	100*	Lorry16t	InertWst	HHHH H--- HRRR
Cloth blind	84	120*	Lorry16t	-	0	-	-	-	16	100*	Lorry16t	DCloth_bld	AAA- A--- ARRA
Coated glass	30	100*	Lorry16t	-	0	-	-	-	70	100*	Lorry16t	InertWst	HHH- H--- HRRR
Fitted carpet	0	-	-	-	95	100*	Lorry16t	Plastic_inc	5	100*	Lorry16t	InertWst	H--- HRR- HRRH
Glass wool	90	100* + 150	Lorry16t Train	-	0	-	-	-	10	100*	Lorry16t	InertWst	LLL- L--- LRRL
Granite tile	80	60*	Lorry16t	-	0	-	-	-	20	100*	Lorry16t	InertWst	MMM- M--- MRRM
Low-emmissivity film	95	160*	Lorry16t	-	0	-	-	-	5	100*	Lorry16t	InertWst	CCC- C--- CRRR
Plaster board	10	100*	Lorry16t	-	0	-	-	-	90	100*	Lorry16t	InertWst	MMM- M--- MRRM
PVC board	80	35*	Lorry16t	-	1	-	-	-	20	100*	Lorry16t	InertWst	HHH- H--- HRRR
PVC frame	71	160*	Lorry16t	-	0	-	-	-	29	100*	Lorry16t	PVCFrame	AAAAAA
Reinf. concrete for slab	80	50*	Lorry16t	-	0	-	-	-	20	100*	Lorry16t	InertWst	MMM- M--- MRRM
Reinf. concrete for facade	80	50*	Lorry16t	-	0	-	-	-	20	100*	Lorry16t	InertWst	MMM- M--- MRRM
Roughcast (Internal)	90	50*	Lorry16t	-	0	-	-	-	10	100*	Lorry16t	InertWst	HHH- H--- HRRR
Steel	95	400*	Lorry16t	-	0	-	-	-	5	100*	Lorry16t	InertWst	HHH- H--- HRRR
Vegetal layer	90	120*	Lorry16t	-	0	-	-	-	10	100*	Lorry16t	InertWst	HHH- H--- HRRR
Waterproofing	90	300*	Lorry16t	-	0	-	-	-	10	100*	Lorry16t	InertWst	FFF- F--- FRRF

Source	Reference	
A	LESO-PB	Calculation made at the Building Physics Laboratory at the Swiss federal Institute of Technology, Lausanne, Switzerland
B	Debrunner SA	Mr. Chappuis, route de Bussigny 29 , 1023 Crissier VD, Switzerland , Phone: +41 +21 637 52 38
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D	Heglas Bulle SA	Mr. Rime, rue de l'Etang 17, 1630 Bulle FR, Switzerland, Phone: +41 +26 919 66 80
E	Pittsburgh Corning	Mr. Fressineau, route de Denges 28G , 1027 Lonay VD , Switzerland, Phone: +41 +21 79 209 21 11
F	Sarnafil SA	Mr. Pillon, rue de Lausanne 14 , 1030 Bussigny-près-Lausanne VD, Switzerland , Phone: Tel. +41 +21 703 22 00
G	Bétonfrais SA	Mr. Nicole, 1422 Grandson VD, Switzerland , Phone: Tel. +41 +24 445 81 11
H	Sotrag	Mr.Cochevnikov, rue du Petit-Chêne 30 , 1003 Lausanne VD, Switzerland , Phone: +41 +79 44 74 101
I	BIRD	Mr. Martaler, route de Renens 2, 1008 Prilly VD, Switzerland , Phone: +41 +21 624 64 94
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L	Flumroc SA	Mr. Niederberger, 1024 Ecublens, Switzerland, Phone: +41 +21 691 21 61
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N	FVE	Mr. Roland Blanc, Fédération Vaudoise des Entrepreneurs, 1131 Tolochenaz, Switzerland, phone: +41 +21 802 88 88
O	Flumroc SA	Mr. Niederberger, chemin de Dallaz 3 , 1030 Bussigny-près-Lausanne VD , Switzerland, Phone: +41 +21 701 57 41
P	Rossier SA	Marbrerie ravalements de façades , chemin des Trois-Ponts , 1024 Ecublens VD , Switzerland, Phone: +41 +21 634 16 85
Q	Alpavert SA	Mr. Grossrieder, au Village , 1628 Vuadens FR , Switzerland, Phone: +41 +26 913 75 40
R	Usine des Cheneviers	M. Amman , route de Verbois 40 , 1288 Aire-la-Ville GE , Switzerland, Phone: +41 +22 727 12 00
Y	Estimation	Estimated data from various sources
-	Data not relevant	
*	The transport distance correspond to twice the real distance, as this mean of transport go back empty at contrary to the other mean(s)	

Q.9 Waste management

Name	Pointer	Description	Unit	NRE [MJ]	GWP [kg CO2-eq.]	AP [kg SOx-eq.]	POCP [kg C2H4-eq.+ NOx]	Reference
Aluminium incineration	*Alu_inc*	Aluminium incineration	kg	1.213E+00	6.256E-02	9.747E-04	1.024E-03	AAAA
Bitume in dump	*BituStab*	Bitume (stabilised dump)	kg	4.984E-01	2.053E-01	7.368E-04	2.014E-04	AAAA
Cloth blind	*DCloth_bld*	Elimination of cloth blind. This average disposal impacts include: steel (hinges) and the cloth in normal dump, and the aluminium (shaft, rails, handle, etc.) in special dump.	kg	4.986E+00	4.861E-01	7.297E-04	3.350E-04	BBBB
Inerte waste	*InertWst*	Inert waste (concrete, un-coated glass, mineral wool, steel)	kg	8.226E-03	5.570E-04	5.289E-06	5.748E-06	AAAA
Mixed wood incineration	*MixWood*	Mixed wood for incineration	kg	2.043E+00	1.208E-01	1.363E-03	1.435E-04	AAAA
PE	*PEInc*	PE for incineration	kg	3.440E-01	2.888E+00	9.336E-04	7.715E-04	AAAA
Polystyren	*EPSInc*	Polystyrene for incineration	kg	3.248E-01	3.037E+00	1.028E-03	7.950E-04	AAAA
Plastic incineration	*Plastic_inc*	Plastic incineration	kg	7.605E-01	2.542E+00	2.786E-03	7.577E-04	AAAA
PVC	*PVCInc*	PVC for incineration	kg	5.163E+00	2.314E+00	2.413E-02	1.281E-03	AAAA
PVC frame	*PVCFrame*	PVC frame elimination (dump). Integrated data, which include all materials elimination.	kg	8.806E+00	8.850E-01	1.290E-03	5.975E-04	BBBB
Stabilised waste	*StabWst*	Stabilised waste	kg	7.183E-01	3.577E-02	2.761E-04	6.949E-05	AAAA
Steel incinerated	*SteelInc*	Steel for incineration	kg	1.098E+00	6.409E-02	8.016E-04	9.355E-05	AAAA
Waste in special dump	*SpecDump*	Waste for special dump (incineration) such as chemical, aluminium spacer)	kg	3.606E+01	3.516E+00	5.277E-03	2.423E-03	AAAA
Wood in dump	*WoodStab*	Treated wood (stabilised dump)	kg	8.834E-01	4.409E+00	3.963E-04	9.995E-04	AAAA
Wood incineration	*WoodInc*	Un-treated wood for incineration	kg	1.710E-01	1.457E+00	6.698E-04	2.762E-05	AAAA

Code	**Reference**
A	ESU [Sut1996]
B	Calculation made at the Building Physics Laboratory at the Swiss federal Institute of Technology, Lausanne, Switzerland

Q.10 Transport process

Name	Pointer	Description	Unit	NRE [MJ]	GWP [kg CO2-eq.]	AP [kg SOx-eq.]	POCP [kg C_2H_4-eq.+ NO_x]	Ref.
Delivery vehicle	*Del_vehic*	30%-loaded	tkm	2.6795E+01	1.6550E+00	9.5397E-03	1.0715E-02	AAAA
Lorry 16 t	*Lorry16t*	40%-loaded	tkm	5.8287E+00	3.7133E-01	3.2046E-03	3.3069E-03	AAAA
Lorry 28 t	*Lorry28t*	40%-loaded	tkm	3.7306E+00	2.2269E-01	1.9125E-03	1.9257E-03	AAAA
Lorry 40 t	*Lorry40t*	50%-loaded	tkm	2.6656E+00	1.4681E-01	1.2567E-03	1.2241E-03	AAAA
Train	*Train*	50%-loaded	tkm	1.0700E+00	5.7400E-02	4.2200E-04	2.6100E-04	AAAA
Intercont. flight	*Inter_Flight*		tkm	1.5400E+01	1.1085E+00	1.1400E-03	5.7300E-03	BBBB
See container	*See_cont*	50%-loaded	tkm	1.3299E-01	8.8805E-03	2.4366E-04	8.7196E-05	AAAA

Code	Reference	
A	ESU	[Sut1996]
B	INFRAS95	[INFRAS1995]

Q.11 Assembly process

Name	Pointer	Description	Unit	NRE [MJ]	GWP [kg CO2-eq.]	AP [kg SOx-eq.]	POCP [kg C2H4-eq.+ NOx]	Ref.
Ass. wood frame	*WoodFrAs*	Assembling wood frame	kg	6.9000E+00	/	/	/	A///
Ass. PVC frame	*PVCFrAs*	Assembling PVC frame	kg	8.5342E-01	/	/	/	A///
Ass. aluminum frame	*AlumFrAs*	Assembling aluminium frame	kg	1.1131E+00	/	/	/	A///
Ass. wood-aluminum frame	*WdAlFrAs*	Assembling wood-aluminium frame	kg	6.6483E+00	/	/	/	A///
Concrete	*Concrete*	Concrete with pump	kg	1.0417E-02	1.5500E-02	1.0000E-04	1.0753E-03	BBBB

Code	Reference	
A	EMPA	[Ric1996]
B	Eyrer	[Eye2000]

Q.12 Maintenance

Name	Pointer	Description	Unit	Maintenance period [y]	NRE [MJ]	GWP [kg CO2-eq.]	AP [kg SOx-eq.]	PS [kg NOx-eq.]	Ref.
Polymer flooring	*PolyFloMain*	Maintenance of polymer floor (PVC, Linoleum, etc.). Includes products and energy for cleaning.	m²	0.16	1.0000E+00	/	/	/	A///
Stone flooring	*StoneFloM*	Maintenance of stone flooring (Granite, ceramic, etc). Includes products and energy for cleaning.	m²	1	1.3000E+00	/	/	/	A///
Synthetic carpet	*CarpetMain*	Synthetic floor maintenance (velvet, fitted). Includes products and energy for cleaning. 2 x week: vacuum cleaner (1000 W, 400 m2/h) + 1 x year: injection cleaning (1500 W, 20m2/h) with synthetic soap (30MJ/m2) and 1100g/m2 water	m²	0.019	4.1000E+00	/	/	/	A///
Wood flooring	*WoodFloMain*	Maintenance of wood flooring. Includes products and energy for cleaning.	m²		1.6000E+00	/	/	/	A///

Code	Reference
A	KBOB2000/1 [KBOB1995]

Q.13 Energy

Name	Pointer	Description	Unit	NRE [MJ]	GWP [kg CO2-eq.]	AP [kg SOx-eq.]	POCP [kg NOx-eq.]	Ref.
Natural gas	*Gas100kW*	Natural gas. Atmospheric < 100 kW	MJ	1.513E+00	8.550E-02	1.010E-04	9.388E-05	AAAA
Electricity CH	*Elect_CH*	Electricity (low voltage) Swiss production (end energy)	MJ	1.748E+00	1.100E-02	8.152E-05	2.003E-05	AAAA
Electricity UCPTE	*Elect_UCPTE*	Electricity (low voltage) UCPTE-mix	MJ	3.555E+00	1.681E-01	1.201E-03	2.441E-04	AAAA

Code	Reference
A	ESU [Sut1996]

Stéphane Citherlet

Birth: 28th December, 1967

Diploma in Physics, EPFL, Lausanne 1991

Research

Leader of the Swiss team in the European project : Implementation of Advanced glazing in Europe (DG XII)
Participation in the European project : Daylighting Design of European Buildings in Europe (DG XII)
Participation in several national projects (Double-skin facade ventilation, predictive control of HVAC systems, etc.)
Advanced simulation and CAL tools development in building physics

Services and Professional Organisations

Chairman and member of the scientific committee of international conferences (*Building Simulation* and *CISBAT*)
Member of the Swiss society of engineers and architects (SIA)
Reviewer for international journals (*Solar Energy* and *Energy and Building*)
Member of the Architecture department board

Professional experience

Since 1998	Lecturer at the Department of Architecture and PhD assistant at the LESO-EPFL. Topic: Integrated simulation in building physics Including 6 months at the Energy Systems Research Unit (Strathclyde University, Glasgow)
Since 1998.	Consultants in building physics for a major engineering company (Bureau G. Monay, Lausanne). Participation in architecture projects in Europe. Several presentations for major construction companies: St-Gobain, Pilkington, etc.
1993 to 1998	Assistant to Prof. Faist and Prof. Scartezzini at the LESO-EPFL.
1992 to 1993	Research engineer at the Energy Systems Laboratory (LASEN), EPFL.

Teaching

2000:	Lecturer in the European Master in Architecture and Sustainable Development
Since 96 :	Lecturer in building physics (Unité d'enseignement UE E), to architecture 3rd and 4th year students
1997 :	Lecturer in building physics to architecture 1st year students.
1993-96 :	Acoustics courses/project supervision (Unité d'enseignement UE F), to architecture 3rd and 4th year students.
1993-96 :	Building physics (exercises) to architecture 1st year students

Publications

15 publications in refereed international journals and conference proceedings
4 contributions to European reference documents
7 contributions to national reference documents
4 lecture notes and didactic documents.

Languages

French: Native language
English: Fluent
German and Italian: Good skills